8-2000

A Methodology and Sampling System for Monitoring Nonpoint Source Pollution from Land Uses

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To the Graduate Council:

I am submitting herewith a thesis written by Bryan Fleet Staley entitled "A Methodology and Sampling System for Monitoring Nonpoint Source Pollution from Land Uses." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biosystems Engineering.

Ronald E. Yoder, Major Professor

We have read this thesis and recommend its acceptance:

C. R. Mote, Daniel Yoder, Paul Denton

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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A METHODOLOGY AND SAMPLING SYSTEM FOR MONITORING NONPOINT SOURCE POLLUTION FROM LAND USES

A Thesis
Presented for the
Master of Science Degree
The University of Tennessee, Knoxville

Bryan Fleet Staley

August 2000

DISCLAIMER

The use of brand names in this thesis does not imply endorsement of these products by The University of Tennessee. The inclusion of manufacturer's names and product models used for this project is only for the purpose of clarification.

DEDICATION

This thesis is dedicated to my parents

Ralph Fleet Staley

and

Lavada Ann Vaughan

who have given me constant support in my educational endeavors and all I have set out to do.

ACKNOWLEDGMENTS

There are many people to whom I would like to express my appreciation for their indispensable assistance in the completion of this project. I would particularly like to thank Dr. Ron Yoder, and the rest of my committee, Dr. C.R. Mote, Dr. Daniel Yoder, and Dr. Paul Denton for their insight and direction in this project. I would also like to thank the following people in the Agricultural and Biosystems Engineering Department, without their assistance this project could not have been done: Richard Roy, John Buchanan, Dr. John Wilkerson, Gary Honea, Paul Elliott, Craig Wagoner, and Walker Garner, and Dr. Arnold Saxton of Statistical and Computing Services..

A number of other people should be recognized for their assistance and kindness in the process of implementing and maintaining the project in Sweetwater: Bob Sliger, Doyle Prince, Derek Starnes and his family, the Hope family, Langdale Pole Treatment Co., David Bryan, and Bowater Land Management Company.

ABSTRACT

Limited research has been done in developing a nonpoint source methodology and monitoring system that enables the quantitative evaluation of land use impacts on water quality in a single watershed. The development of a methodology and sampling system that specifically targets the runoff component of streamflow is important in determining which types of land uses contribute most to water quality degradation. In addition, an established monitoring strategy and sampling system will provide for the collection of water quality data when the pollution potential is greatest.

Both a monitoring methodology and a computer controlled sampling system have been developed that utilize flow proportional stream sampling based on hydrograph slope. A 6,216-ha (24-mi^2) watershed in eastern Tennessee was used as a case study to evaluate effectiveness of both the NPS monitoring methodology and sampling system. The methodology developed provided an effective analysis of the watershed for NPS pollution potential; however, field operation of the sampling system proved problematic due to the type of computer used despite successful laboratory testing. More research is needed in order to further test and develop an appropriate nonpoint source sampling methodology and system that is founded on the mechanisms driving the addition of pollutants into the watershed system.

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Chapter 1

Introduction

Significant degradation in our nation's water quality can be attributed to nonpoint source pollution (EPA, 1992). Nonpoint source (NPS) pollution can be defined as the degradation of water quality from any nondiscrete, indiscernible, unconfined source. Because NPS pollution does not emanate from a single point, it is more difficult to quantify and identify than point source pollution. However, NPS pollution can be directly attributed to land uses within a particular watershed (Tokarski and Genetelli, 1990). In 1992, the Environmental Protection Agency reported the two leading causes of NPS pollution were agriculture and urban runoff/storm sewers.

In recent years, NPS pollution has become the focal point in efforts to reduce surface water pollution. Monitoring must be performed in such a way as to identify the primary mechanisms causing the pollution. These primary mechanisms can then be manipulated to reduce pollution through controls such as best management practices, change in land use, and other pollution prevention efforts. Activities impacting land uses, topography, and other watershed characteristics will have a positive or negative effect on water quality; as a result, these characteristics must be considered in the monitoring and evaluation of nonpoint source pollution. Therefore efforts to monitor water quality that focus only on portions of a watershed may not effectively determine the primary mechanisms or sources causing the pollution.

With this idea in mind, the watershed and the bodies of water in the watershed can be viewed as an ecological system, and a more effective effort can be made in evaluating the mechanisms causing water quality degradation and in accurately monitoring water quality changes. Approaching the problem in a holistic sense such as this can aid in implementing more effective monitoring to locate and reduce NPS problem areas within a watershed. The important idea behind the examination of NPS pollution is that any stream, river, or lake is not a single, stand-alone entity. These bodies of water receive inputs (e.g., sediment, runoff, groundwater contribution, etc.) from the entire watershed that affect water quality. Nonpoint source pollution must be examined in a more holistic sense where factors and mechanisms attributing to pollution are examined over the entire watershed.

In utilizing this holistic approach to monitor and reduce NPS pollution, three factors must be considered:

1) The mechanisms and driving forces in place (e.g., hydrology, meteorology, etc.) play a vital role in water quality degradation.
2) The methods and technology used to evaluate NPS pollution processes can significantly affect the results obtained.

3) The collection/evaluation of information on these processes and pollutants is extremely important in accurately determining impacts on water quality.

The effectiveness of these three factors in the design and establishment of a monitoring framework will determine whether or not the results obtained accurately reflect the degree of water quality degradation occurring in the watershed.

FACTOR 1: The primary mechanisms and driving forces in a watershed such as land use, hydrology, and meteorology determine the amount of pollution seen at the watershed outlet. The first question that must be answered, is that regardless of the mechanisms determining the quality of water exiting a particular watershed, what is the overall driving force behind everything occurring in the watershed? The answer is the water itself, or more specifically, the movement of water through the watershed. The way water moves (watershed hydrology) and the amount of water moving through a watershed (meteorologic and groundwater characteristics) determine on a basic level the outgoing water quality at the outlet of the watershed. Granted the outgoing water quality also depends on other factors such as the quantity of pollutants that exist in the watershed and whether or not they can be transported into a body of water; however, without the movement of water the primary means of access for pollutants into the aquatic system is removed.

The primary mechanism affecting the movement of water through a watershed is land use. All water that moves over and/or under land surfaces at one time originated as rainfall; therefore, the quality of water is strongly affected by the characteristics that define the land use. For example, research has shown that both agricultural and non-agricultural land uses contribute to pollutant loading in surface waters of the U.S. Spooner et al. (1991) found that phosphorus and nitrogen loading (in streams) can be attributed primarily to agricultural land use. Nelson and Ehni (1976) stated that "Agriculture possesses the greatest potential for affecting the quality of the nation's water resources." Research performed by Maas et al. (1985) determined that the most common pollutants from agricultural areas are: sediment, nitrogen, phosphorus, and pathogens.

Nearing et al. (1993) stated that while agricultural nonpoint sources contribute to daily nutrient fluxes, non-agricultural nonpoint sources contribute about one-half the total nutrient load based on a study examining streams entering Lake Lanier, Georgia. Urban areas contribute a wide array of pollutants. Typically the primary urban pollutants are metals, toxic chemicals, and lawn/garden fertilizers according to Charbonneau and Kondolf (1993).

There has been a significant amount of research performed comparing how land use contributes to nonpoint source pollution. However, very little research has been performed that monitors runoff from land uses to determine whether one land use contributes more to water quality degradation than another. Does one particular land use contribute more to water quality degradation than another, given similar hydrologic and meteorologic conditions? Most research on this front has only compared two land uses. Many times these land uses were not in the same watershed or the data collected was not very complete. For example, Frink and Norvell (1976) found that residential land can contribute up to three times the phosphorus (by mass/acre) when compared to agricultural land. Consequently, results obtained from the research performed can reflect error in the type of NPS monitoring used. As a result, accurately quantifying pollutant loading through effective monitoring techniques is extremely important.

The characteristics that define a land use are primarily the type of cover, amount of impervious area and dynamic impacts (e.g., impacts from humans, animals, traffic, etc.). These characteristics can be categorized to be broad or specific depending on the level of complexity desired and the objectives of the project. The land uses are delineated based on the uniformity of these characteristics. Examining NPS pollution by land use delineates sub-watersheds within the watershed by primary land use, or land uses. In this way, relative effects of each land use on water quality can be determined.

Meteorological and hydrological factors are the driving forces behind the movement of water; however, two controllable land use related mechanisms can be attributed to causing NPS pollution: soil disturbance and coverage by impervious surfaces (Byron and Goldman, 1989). Disturbing or changing the natural flora and soil can make it much easier for pollutants to be dislodged and transported to a body of water during a runoff event. Soil characteristics such as porosity can detain water moving through the soil profile and physiochemical interactions between the pollutants and the soil particles tend to purify water during its movement through the soil. In addition, the infiltration and storage capacity of the soil result in less runoff than from impervious surfaces (e.g., roads, parking lots, buildings, etc). On impervious surfaces, pollutants tend to build up until a sizeable rainfall event causes enough runoff to transport them to surface water.

On a small watershed comprised mainly of dairy farms, it was found that animal density directly impacted fecal bacteria counts in streams but did not influence sediment or nutrient concentrations (Meals, 1992). The impact from the dairy animals is highly variable depending on the number of animals per unit of field area. The more animals the greater the impact on water quality. This is a dynamic variable that depends primarily on the use of the land. A similar situation in an urban setting may be the number of vehicles traveling through the watershed.

Another dynamic variable is the use of pesticides and other chemicals. Pesticide concentrations in the streams of agricultural land uses are highly dependent on the amount applied and the mode of application. Pesticide concentrations do not necessarily depend on sediment concentrations but seem to depend on factors such as rainfall, time since application, soil type and moisture condition, crop condition, temperature, and characteristics of the pesticide (Richards and Baker, 1993).

In addition, effective monitoring of NPS pollution from distinct land uses can aid in determining whether certain land uses are a consistent problem, or are only a problem during storm events or certain times of the year (impacts due to seasonal variation).

Since agricultural activities typically disturb large tracts of land they can be a serious threat to water quality. Due to this, best management practices (BMP's) are extremely important, according to Shirmohammadi et al. (1994), in reducing the potential for water quality degradation. A typical best management practice essentially creates a buffer area between a land use reducing runoff pathways that could potentially affect the water quality of a body of water. Ritter et al. (1989) found that proper use of BMP's resulted in decreased total suspended solids and total phosphorus while no change was seen in nitrogen loads. This occurred in a 12,459-ha (30,787-acre) watershed comprised primarily of cropland. This research suggests that BMP's are effective in reducing sediment loading on streams since many common forms of nitrogen are very soluble whereas phosphorus is not, and is typically attached to soil particles. However, very little research has been performed to determine when most of the sediment loading occurs. For example, if a majority of NPS pollution from agricultural land or other land uses occurs during storm events, BMP's could be implemented that specifically address pollution occurring during storm events. Other factors such as irrigation also need to be considered.

Water table fluctuations can affect streamflow, which in turn can have an effect on water quality. A streamflow that is lower than normal could result in less dilution of pollutants in the runoff that enters the stream. This would increase the concentration of the pollutant(s) in the stream which may result in adverse affects to the aquatic system such as a fish kill.

FACTOR 2: Consideration of the hydrologic system, areal differences, and meteorologic variations must be a primary factor if accurate characterization of water quality is desired; however, these considerations typically have been peripheral in establishing a foundation upon which sampling methodology rests for nonpoint source pollution. The methodology and techniques used to determine the amount of NPS pollution can provide differences in results because they may not effectively correlate NPS pollutant loading to the mechanisms and driving forces mentioned above (Factor #1).

If NPS pollution can be effectively linked to watershed hydrology and meteorology, NPS pollution can be adequately controlled because we will be able to:

- accurately predict the extent of NPS pollution within a watershed,
- model NPS pollution on watersheds with changing land use conditions, and
- determine highly effective ways to manage and control NPS pollution.

Unfortunately water quality monitoring can be very complex because the monitoring strategy and sampling equipment used can provide results that can overestimate, underestimate, or skew the pollutant loading that is actually occurring. This can result in ineffective or improper use of strategies and methods for assessing water quality degradation.

To clarify this, the American Society of Testing and Methods (ASTM, 1985) "Standard Practices For Sampling Water" (D3370-82) lists three methods for sampling water. Each method is listed below with its description.

1) *Grab Sample* - Each sample is taken at a specific site which represents the conditions of the body of water only at the time of sampling.
2) *Composite Sample* - Samples are collected at a specific site over varied time intervals or alternately at various sites and/or times.
3) *Continual Sampling* - This type of sampling provides a continuous flowing sample from one or more sampling sites suitable for on-stream analyzers.

   (Author's Note: This type of sampling as described in ASTM D3370-82 is primarily

referring to in-situ analysis of the water to provide an instantaneous result or compositing a sample over a specific time or flow interval).

It should be evident, by examining the definitions of the sampling methods described above, that the results obtained from a particular monitoring event have the potential to vary widely simply due to the method of sampling used. For example, if a slug of pollutant were released into a stream where all three of the above methods were used at the same site, very different results could be obtained depending on the monitoring strategy utilized. If the grab sample were taken just prior to the slug going past the sampling site, a minimal or slight increase would be noticed in pollutant levels. The composite sampling would show that a slug of pollutant went past the sampling site but would dampen out or underestimate the duration and/or maximum concentration of the slug. In all probability the continual sampling could fully characterize pollutant loading provided the pollutant being considered can be measured in the field using an "in-situ" analyzer (i.e., a device that can provide an immediate analysis of a pollutant during continuous flow).

Current technology cannot provide an "in-situ" analysis of all pollutants typically monitored to characterize water quality; however, continual sampling would probably best characterize the slug if the sample duration and the time interval between sampling coincided well with the duration and peak concentration of the pollutant plug passing the sampling location. As a result, entirely different conclusions may be drawn from the three sampling methods that characterize, with varying degrees of accuracy, what actually occurred. The results obtained from these three methods can be highly variable depending on the number of samples collected and the time interval at which they are collected.

Therefore, the development of monitoring strategies and sampling technologies that are consistent and based on hydrologic, meteorologic, and watershed characteristics should allow NPS impacts on water quality to be defined more accurately. This refinement in monitoring strategy and sampling technique will provide results that are reproducible within a defined watershed and will provide a possible standard by which water quality can be measured.

Current monitoring strategies and methods rely heavily on timed and/or grab sampling to determine the amount of pollutant loading for a particular watershed, stream, or stream reach. These methods are employed primarily because of their cost effectiveness. While these sampling procedures can provide an indication regarding whether or not pollution is occurring, no accurate estimate of the degree of pollution occurring can be determined. This is because timed or grab sampling techniques do not take into account the hydrologic and meteorologic factors affecting pollutant loading. As a result, a sample taken from a stream during a high flow event where a major component of the flow is runoff may show high pollutant concentrations that are not indicative of pollutant concentrations existing during normal flow (baseflow).

Technology does allow for some hydrologic and meteorologic variables to be measured and used with available sampling equipment in order to characterize dynamic pollutant loading by controlling and recording data through the use of a computer. Such an approach is used in this project and is described in detail in Chapter 5.

FACTOR 3: Information collected on hydrologic and meteorologic factors, pollutant concentrations, and land use can aid in better understanding of the processes resulting in NPS pollution. The duration and frequency at which this information is collected will have a direct result on the accuracy of the results obtained.

The best results in water quality research have been obtained by collecting information for relatively long periods of time. In many instances it can take as long as three to five years to establish definite changes in water quality. The primary reason for this is that the parameters tested are typically quite variable. More intensive monitoring could reduce a significant portion of this variability by isolating variation due to storm events, seasonal variation, and land use changes.

The extent of possible research topics within the realm of nonpoint source pollution are many. The focus of this thesis is to utilize the holistic approach described previously in developing a methodology and sampling system to monitor NPS pollution from specific land uses.

There are three primary reasons to monitor NPS pollution from specific land use:

1. A better understanding of the role of land use in NPS pollution is needed.
2. Improved NPS pollution sampling practices are needed.
3. Limited information has been collected, or research conducted, to determine how the quantity of water flowing from different land uses affects the quality of water.

A better understanding of how land uses affect water quality is paramount to understanding the primary mechanisms of nonpoint source pollution. Although strong correlations have been made relating pollution to land use, information is needed regarding how much pollution various land uses contribute (i.e., better monitoring practices), what kind of pollutants are emitted from each land use, and which land uses can be improved to reduce the amount of pollutants entering bodies of water. Once specific land uses have been identified as primary contributors, steps can be taken to determine what factors within that particular land use are causing the pollution.

The second reason to examine land use impacts is that there has been a limited amount of data collected relating NPS pollution to land use and comparing NPS pollution between land uses. Typically two opposing factions exist regarding the sources of NPS pollution. One faction supports the idea that most NPS pollution is due to agricultural practices while the other claims that urban areas cause most NPS pollution. Based on past and present research, neither land use has had a positive impact on the environment. The amounts of data obtained have been quite helpful in determining whether or not NPS pollution exists; however, more information is needed in order to determine more accurately the amount and timing of pollutant loading.

Despite the best intentions and efforts in solving the problem of NPS pollution, little will be achieved until sampling practices are implemented that quantify NPS loading of pollutants in runoff and in streams. To identify the magnitude of the NPS problem one must know how much and when a pollutant comes off a land use area (i.e., more intensive sampling efforts). Only then can practices be implemented that will most effectively reduce, or remove, NPS pollution.

The most commonly employed sampling practices in use today do not take into account factors such as watershed size, watershed shape, vegetation, impervious area, slope, soil type, buffer zones, stream flow, channel characteristics, rainfall, and groundwater contribution. With more intensive sampling efforts at appropriate times, it is hoped that pollution sources can be narrowed to specific stream reaches, or tributaries, within a land use or watershed. If this can be achieved nonpoint source pollution should be more easily controlled, reduced, or eliminated.

By looking at how land use affects water quality and basing the monitoring strategy on the driving forces and mechanisms in the watershed, this project[1] examines a unique approach that has the potential to quantify water quality degradation more discretely and more accurately.

One component of this approach is analyzing constituents in the samples taken on a mass per watershed area basis, or on a concentration basis. For this project, constituent levels have been calculated on a mass per watershed area basis.

Mass vs. Concentration

There are advantages in monitoring NPS pollution based on the mass of pollutants rather than their concentration. The most important advantage is that variability due to runoff volume or streamflow can be eliminated.

The concentration of a pollutant is based on two things: the amount of pollutant in the liquid and the volume of liquid that receives the pollutant. If an analysis of pollutant

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[1]Funding provided by the Tennessee Agricultural Experiment Station.

loading is made based on pollutant concentration an error could be made in how much each land use is contributing. To illustrate this point please refer to the following example.

Consider a situation where two watersheds of the same shape and size are examined to determine how much of a particular pollutant is coming from each. In this example, one sample was taken from each watershed (at the outlet) and the flow measured at the outlet of each watershed. Assume Table 1 displays the results obtained from the measurements:

If concentration is considered it would appear that Watershed 1 is contributing more pollutant to the stream than Watershed 2. Calculating the pollutant loading on a mass basis by multiplying the pollutant concentration by the flow rate and dividing by the watershed area gives a mass loading for Watersheds 1

Table 1: An example of pollutant loading/flow from two watersheds with the same area.

Measurement	Watershed 1	Watershed 2
Pollutant Concentration	10 mg/L	5 mg/L
Flow	0.4 m^3/s	0.85 m^3/s

and 2 of 15.3 mg/ha-s and 16.4 mg/ha-s, respectively. Watershed 2, while having a lower concentration, actually is contributing more pollutant per unit area than Watershed 1.

From this example it is easily seen that the volume of runoff or streamflow can affect the ***amount*** of pollutant being transported from a land use. Therefore, comparing pollutant loading from land uses based on mass rather than concentration should result in a more accurate analysis.

There are a few disadvantages in calculating pollutant loading on a mass basis. Some changes in pollutant loads will be a function of stream characteristics. For example, volatilization of nitrogen in the stream will be a function of stream characteristics such as surface area, the amount of nitrogen in the stream water, and aeration. The loading or transport of some less soluble pollutants will also depend on stream velocity and channel shape. In addition, changes in baseflow can skew results if the goal is primarily to quantify contributions due to runoff from land uses.

The mass of pollutant from land uses in this project was calculated using the following equation:

$$M = (C * Q)/ A \qquad \text{[Eqn. 1]}$$

where M = mass per unit area per second (g/ha-s)

C = concentration (mg/L)

Q = average stream flow or flow at time of sampling (m^3/s)

A = watershed area (ha)

This equation converts concentration to mass loading in SI units.

Chapter 2

Project Objectives and Description

The objectives developed for this project are based on the holistic approach described in Chapter 1. In this approach, the entire watershed is examined and causal factors that contribute to water quality degradation are identified throughout the watershed. By analyzing the entire hydrologic system, pollutants causing water quality degradation can be traced from their introduction into the watershed to their incorporation into a body of water.

The overall focus of this project is intended as initial research to explore new monitoring methods for NPS pollution and to collect preliminary data in order to validate the monitoring strategy. It is recognized that there are three necessary components to effectively and accurately determine NPS impacts on water quality: an appropriate monitoring strategy, an effective sampling system, and proper evaluation of the mechanisms causing NPS pollution. This project ties these three components together.

Three specific objectives were determined for examining nonpoint source impacts on water quality due to land use:

1. To establish a strategy for monitoring nonpoint source pollution.
2. To develop a sampling system to sample streams affected by NPS runoff.
3. To test the sampling system in the field and use any data collected to demonstrate system performance.

OBJECTIVE #1: Monitoring Strategy

First, a monitoring strategy is needed to adequately quantify the nonpoint source runoff component in streams during storm events. The monitoring strategy must be based on watershed hydrology and meteorology so that sampling is dictated by the hydrologic conditions affecting the stream. A monitoring strategy should answer the questions of where to locate sampling stations within a watershed and when to take samples. The monitoring strategy was designed to monitor significant runoff from land uses and to take more samples during sizeable rainfall/runoff events when nonpoint source pollution is most likely to occur. This type of sampling strategy characterizes the extent of runoff occurring because more sampling is performed as the runoff component of the stream gets larger during a storm event.

There is a strong correlation between runoff and nonpoint source pollution. Runoff is generated when the rainfall intensity during a storm exceeds the intake rate of the soil and the storage capacity of the soil surface. As the rain water collects and ponds up on the land surface, pollutants deposited from various sources are dissolved or dislodged and carried by the runoff. As these ponded areas overflow, runoff carries these pollutants via overland flow, storm drains, waterways, and similar paths to streams and other bodies of water. Depending on the volume of runoff and size of the body of water accepting the runoff, the runoff can have a significant effect on the water quality of that body of water (Beasley et al., 1984).

Basing a monitoring strategy on the hydrologic characteristics and runoff potential of the land use establishes a foundation on which to develop a procedure for making decisions on the most practical and effective way to monitor NPS pollution. Such a strategy provides an appropriate degree of complexity for the specific project at hand.

OBJECTIVE #2: Sampling System

The most widely used sampling methods employ one or more of the techniques described by the ASTM (1985) paper "Standard Practices For Sampling Water" (D3370-82) or a variation of these techniques. As described in Chapter 1, standard sampling practices are either grab, composite, or continuous. For this project, a variety of sampling methods was considered to determine which methods may be best suited to this application and may provide the best information possible.

Schaap and Einhellig (1994) employed sampling techniques similar to those described above in order to characterize differences in water quality between stormwater runoff and stream flow during no storms events. In their study, grab samples were collected during the first hour of the runoff event and flow-weighted composite samples were taken at 15-minute intervals during the first 3 hours of the event, or until the discharge returned to normal flow levels.

Stillwell and Bailey (1993) evaluated the practicality of manual stormwater sampling to comply with current regulations governing National Pollutant Discharge Elimination System (NPDES) permit applications. They found that manual sampling is extremely labor intensive, potentially unsafe for personnel, and hard to perform in conditions of darkness or inclement weather. Regulations require that samples be taken prior to the storm, during the first 30 minutes of the storm (for a first flush sample), and a flow weighted sample taken every 15 minutes for the duration of the storm, or for 3 hours (whichever is less). They suggested that automated sampling be used as an alternative to manual sampling to provide more reliable data and to reduce the potential for injury to personnel.

Denning et al. (1991) found that a flush of "soil solutions" into the surface water occurred at the beginning of the runoff event (in this case a snowmelt). The study suggests that this flush of constituents could have a profound impact on the degree of pollutant loading in a stream, especially non-soluble constituents. The sampling practices given by ASTM do not provide an effective technique for sampling the first flush. As a result, the ASTM practices must be modified in order to adequately sample and characterize the mass of pollutants entering a stream from this flush of constituents from a particular land use by taking samples more frequently during the first flush.

Burwell et al. (1975) determined that “changes in the chemical concentration and water discharge with time are prime factors of concern in establishing frequency of sampling required.” They found that the variations of these two factors can be attributed to the movement of chemicals from land to streams via runoff and erosion processes. Therefore it is important to sample the stream not only during periods when no runoff is occurring but also during periods when runoff is significantly contributing to stream discharge.

Roman-Mas and Diehl (1991) worked on optimizing a sampling strategy to assess agricultural nonpoint source pollution. The study was performed in west Tennessee on the Beaver Creek watershed near the town of Mason. The primary focus of their effort was in characterizing suspended sediment concentrations during storm events. They found that sampling every 5 minutes during the rising limb of a storm hydrograph and every 15 minutes on the falling limb provided enough sensitivity to accurately characterize pollutant loading. This suggests that much more dynamic pollutant loading is occurring during the rising limb of the storm hydrograph than at any other time. Therefore a higher sampling frequency is needed to catch the first flush of pollutants and other changes in loading as each portion of the watershed begins contribute to the overall pollutant load.

OBJECTIVE #3: Field Testing the Sampling System to Demonstrate System

Performance

To date, a relatively small amount of research has been performed on sampling NPS pollution from land uses. Many of the studies that have been conducted have dealt primarily with minimal sampling to compare effectiveness of best management practices (Spooner, 1993). In an effort to isolate nonpoint source pollution, the first step is to discover where in the watershed it is occurring, and then to determine the appropriate course of action (i.e., best management practices, erosion controls, etc.) to alleviate the problem. A summary of past research performed relevant to this project is described below. The review of research within this objective has two focuses, the first focus is on land use activity and its correlation to nonpoint source pollution; the second is on how much nonpoint source pollution occurs during "normal" conditions and conditions of runoff during a storm event.

A study performed by Farrell-Poe and Ramalingam (1994) in the town of Wellsville, Utah showed that a rural municipality consistently added fecal coliform bacteria to an adjacent stream (approx. 100 cfu/100 mL added excluding extreme events) during a year-long study. The highest loading of fecal coliform (about 900 cfu/100 mL added) was seen during a 4.1 cm rainfall. Additions of nitrate-nitrogen and phosphorus (ortho-phosphorus) during the entire study were approximated at 0.25 mg/L and 0.20 mg/L, respectively. The town of Wellsville, Utah covers approximately 280 ha (1.1 mi^2).

The effects of unconfined livestock activities on water quality were evaluated by Robbins (1979). It was found that the degradation of water quality is primarily dependent on hydrogeological and management factors. Sedimentation caused by erosion appeared to have the highest potential for polluting bodies of water.

In a related study, Thelin and Gifford (1983) performed a study on fecal coliform release patterns from fecal material in cattle grazing areas. The study showed that the presence of fecal coliform bacteria in streams can be attributed to grazing livestock, but the potential for nonpoint source pollution is based on stocking density, length of grazing period, average manure loading rate, manure spreading uniformity by grazing livestock, and disappearance of manure with time. Therefore the extent of nonpoint pollution that may occur can be dictated largely by management practices, the location of the stream in proximity to the pasture, and the amount of runoff occurring during a storm event. The study did not consider situations where livestock stood in the stream. Therefore agricultural or rural land uses having significant percentages of grazing pasture have a potential for introducing fecal coliform bacteria into adjacent or nearby streams.

An environmental impact statement prepared jointly by the Tennessee Valley Authority, the U.S. Army Corps of Engineers, and the U.S. Fish and Wildlife Service regarding chip mill terminals on the Tennessee River revealed that mature forested areas have little impact on water quality other than the addition of organic matter and some sediment. The degree of sedimentation was found to be dependent on topography.

A study on urban stormwater runoff contamination of the Chesapeake Bay (Lee and Cameron, 1992) found that urban sectors in Montgomery and Prince George's County (Maryland) contribute more, or the same amount, of nutrients than non-manured farmland. The study showed that urban stormwater runoff is comparable to the quality of point source discharges from sewage treatment plants and large factories.

A stormwater quality study performed by the EPA for New Castle County, Delaware found that higher flow in the stream due to urban runoff did not dilute point source pollution but in fact caused the water quality to be worse than during normal flows. The water quality downstream of urban areas was found to be controlled by point sources 20 percent of the time. The primary pollutants found in urban runoff were total solids, oxygen demand (BOD_5 and COD), nitrogen, phosphorus, bacteria, and heavy metals. Water quality degradation in rural and agricultural areas was primarily due to sediment, nitrogen, and phosphorus while water quality degradation from forested areas was due mainly to organic matter.

The project described in this thesis ties together three vital components in assessing nonpoint source pollution: an effective monitoring strategy, an adequate sampling system, and an assessment of functionality of the sampling system in the field. Completion of the project's objectives resulted in a systematic methodology of assessing nonpoint source pollution on a watershed scale. This methodology or system will provide a nonpoint source pollution impact assessment of any watershed.

Chapter 3

Project Location - Watershed Selection

The first step in utilizing this holistic approach to examine monitoring strategies and sampling techniques for NPS pollution was to select a suitable watershed with the desired land use characteristics to implement the project. The site was then assessed in order to implement an effective monitoring strategy. For this project, the watershed was defined as the entire watershed that encompassed all land uses and sub-watersheds. Sub-watersheds were defined as the areas, or land uses, within the entire watershed that were monitored.

Criteria For Watershed Selection

A watershed was chosen that would be large enough to possess a wide range of land uses, yet be small enough to be managed relatively easily. The criteria in the selection of a suitable watershed for this project were as follow:

1. The watershed should have no “abnormal” or distinct pollution problems. The watershed should be analogous to other watersheds of similar size in the region with no large point source inputs or other characteristics that are atypical of the rest of the watershed.

2. The watershed should contain a number of land uses, including agricultural and urban components. The watershed should have a variety of common land uses typical of other similar sized watersheds in the region.

3. Land uses within the watershed should be as distinct and separate as possible in order to provide data that is associated with only one distinct land use (if possible), and

4. All land uses should be located, preferably, on the same stream within a watershed. Land uses that are adjacent to each other and located on the same stream allow them to be compared sequentially downstream. In this manner, pollutant contributions from each land use can be compared to determine the effect of a single land use on overall stream water quality.

Of three candidate watersheds examined for this project, the upper Sweetwater Creek watershed, which includes the town of Sweetwater, Tennessee, provided the best land use separation and also had a woodland land use (the others did not). This watershed was relatively "normal" in that no distinct or extreme pollution problems existed. There were no large point sources that could potentially skew project results. The upper Sweetwater Creek watershed is approximately 6,216 ha (24 mi^2) in area.

The selection of a suitable watershed for the project was based on extensive time spent surveying the watershed in consideration of the criteria given above; however, each sub-watershed possessed a distinct set of characteristics. Therefore, the selection of a suitable watershed involved a degree of subjectivity.

Watershed Location and Comparability

The Sweetwater Valley, which runs parallel to Interstate 75, is located approximately half-way between the cities of Knoxville and Chattanooga, Tennessee. Figure 1 shows the project location. With the exception of the town of Sweetwater, the area is predominantly rural, containing primarily farmland and woodland. Residences are spaced sporadically along primary and secondary roads. The town of Sweetwater contains industries and businesses such as a pole treatment company, hosiery mill, furniture manufacturer, saw mill, tobacco co-op warehouse all within a 259-ha (1-mi^2) area (approximate). Small industries such as these are rather common in most small to middle sized watersheds in eastern and middle Tennessee.

Sweetwater Creek is one of the primary drinking water sources for the town and is also used for some irrigation of farmland and for industrial purposes. Parks and recreational areas on the banks of Sweetwater Creek in the town provide somewhat of a buffer zone between the stream and the city streets. Main Street runs parallel to the creek (along its west bank). The largest concentration of residences near the stream is

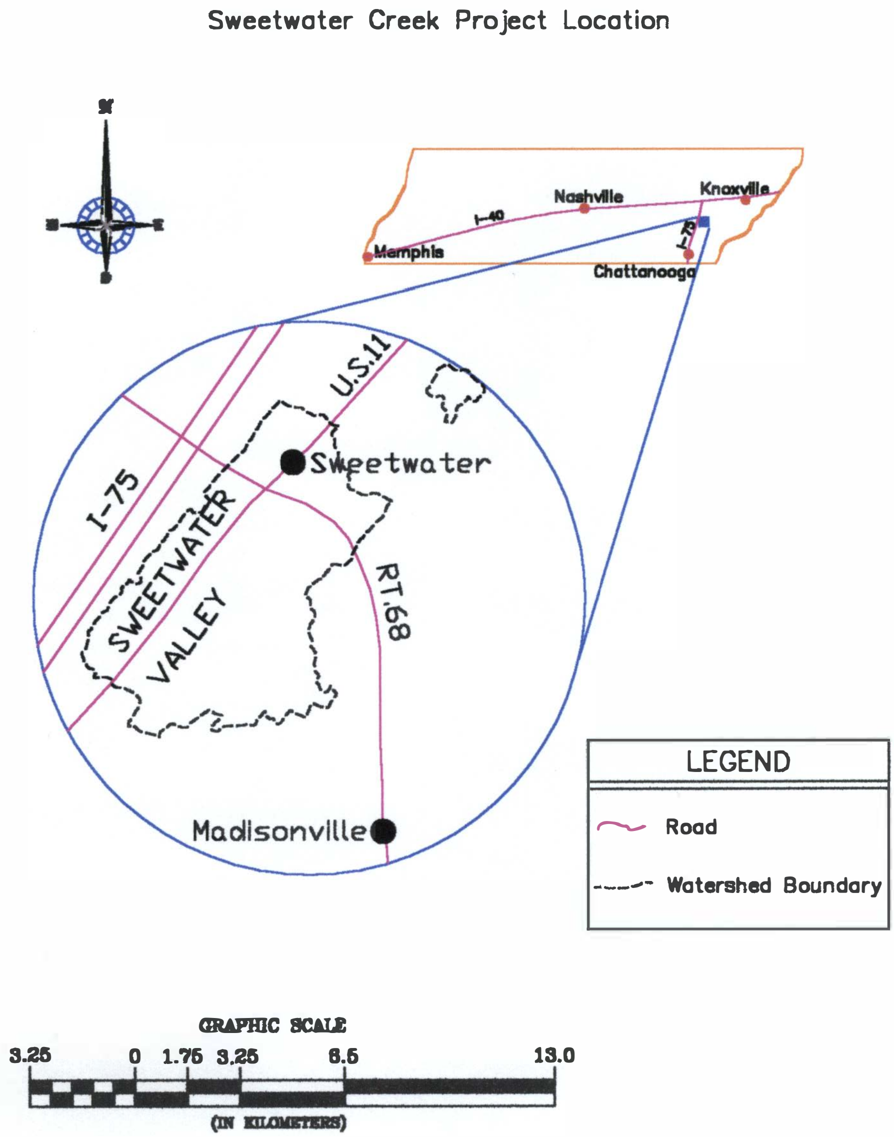

Figure 1: The general location of the site is between Knoxville and Chattanooga, TN.

located on a hill (on the west bank) overlooking the creek. Many of the industries are also located along the banks of the creek. The town utilizes a wastewater treatment plant to treat domestic waste water and residents outside the city limits utilize septic tanks.

Sweetwater Creek's narrow banks have caused excessive flooding over the years; as a result, crops, homes, and businesses have been damaged. Due to this, the Soil Conservation Service (now the Natural Resource Conservation Service) installed a series of flood control reservoirs in the mid 1980s.

The Sweetwater Valley area rests on a primary strata of limestone, dolomite, and shale and parts of this region are characterized by karsts and caves. Karsts and caves in conjunction with folded and faulted formations cause areas of interior drainage or outflow. This results in a surface/groundwater interaction that is quite complex (USGS, 1983). As a result, land use effects on water quality have the potential to be seen not only in surface waters but also in groundwater. Despite the potential for surface/groundwater interaction, no significant areas of interior drainage or outflow were noted during numerous visual inspections of the watershed. Further research may provide insight as to how groundwater is being affected by surface runoff. For the purpose of this project, only surface water has been examined.

Delineation of Sub-Watersheds

Past efforts in delineating land uses have been based on characteristics such as impervious area, concentration of buildings, type of vegetation, etc. Because of this, determining which land use is considered "rural" and which is considered "urban" can be relatively subjective. As a result, the criteria used to delineate the land use must be defined. For the purposes of this project, five major land uses were identified within the watershed.

Each land use and its definition is listed below.

1. *Rural:* The area is characterized primarily by residences with a concentration of 1 house/ 3 acres or less (on average), very little impervious area, very few businesses, and the presence of some small and mid-sized farms. The area also contains tracts of wooded land too small or broken up to be defined as a woodland (continuous forest).

2. *Agricultural:* The area consists primarily of farms, pasture, cropped land, or other types of agricultural use. There is practically no impervious area in this land use. Small areas within this land use may meet the definition of a rural land use but such areas are not greater than 10.1 hectares (25 acres). This area contains tracts of woodland primarily along field/pasture borders and streams in areas where topography makes the land non-farmable.

3. *Mixed:* This area is primarily a transitional area between rural and urban land uses. The concentration of houses still meets the 1 house/ 3 acres or less average criterion, but the area also contains small apartment complexes and townhomes. The area also contains a much larger percentage of businesses, shopping centers and industry. The extent of impervious area is much larger than the rural land use due to parking lots, roads, and large roofed structures.

4. *Urban:* This area consists primarily of business, industry, and residences with a concentration of 1 house or building/acre or more. Much of the area is impervious.

5. *Woodland:* This area is nearly completely forested with the exception of small pockets of meadows. Any existing residences in this land use have a concentration of 1 house/200 acres or less. No businesses or farms are present.

The land uses identified for this project proceed sequentially downstream starting with the rural land use at the headwaters of Sweetwater Creek, followed by the agricultural, mixed, and urban land uses. The woodland use is not located on the main stem of Sweetwater Creek, but is on one of its tributaries. Although this does not provide for a sequential procession between the woodland and other land uses, the data provided useful information on the water quality from a woodland land use. Even though the watershed selection criteria was not met for this one land use, the Sweetwater Creek watershed met more of the criteria than the other watersheds that were considered. A map of the entire watershed area is seen in Figure 2. Table 2 shows the relative percentages of each land use within the watershed. The agricultural land use was added late in the project and is presented here only for illustrative purposes. Results from the agricultural land use are not included in this thesis.

Primary Pollutants From Sub-Watersheds

By identifying major pollutants, an interpretation can be made as to how effective the monitoring system characterizes pollutant loading. However, not all cases are quite so simple. For example, if heavy metals are found to be a problem with one sub-

Table 2: Relative percentages of each land use with the watershed and sub-watersheds.

Land Use	Sub-Watershed Area (ha)	% Total Watershed Area
Rural	1,166	18.8
Agricultural	1,943	31.2
Mixed	1,295	20.8
Urban	1,632	26.3
Woodland[1]	182.0	2.9
TOTAL	6,218	100.00

[1]Note: This watershed is separate from the main watershed (see Figure 2).

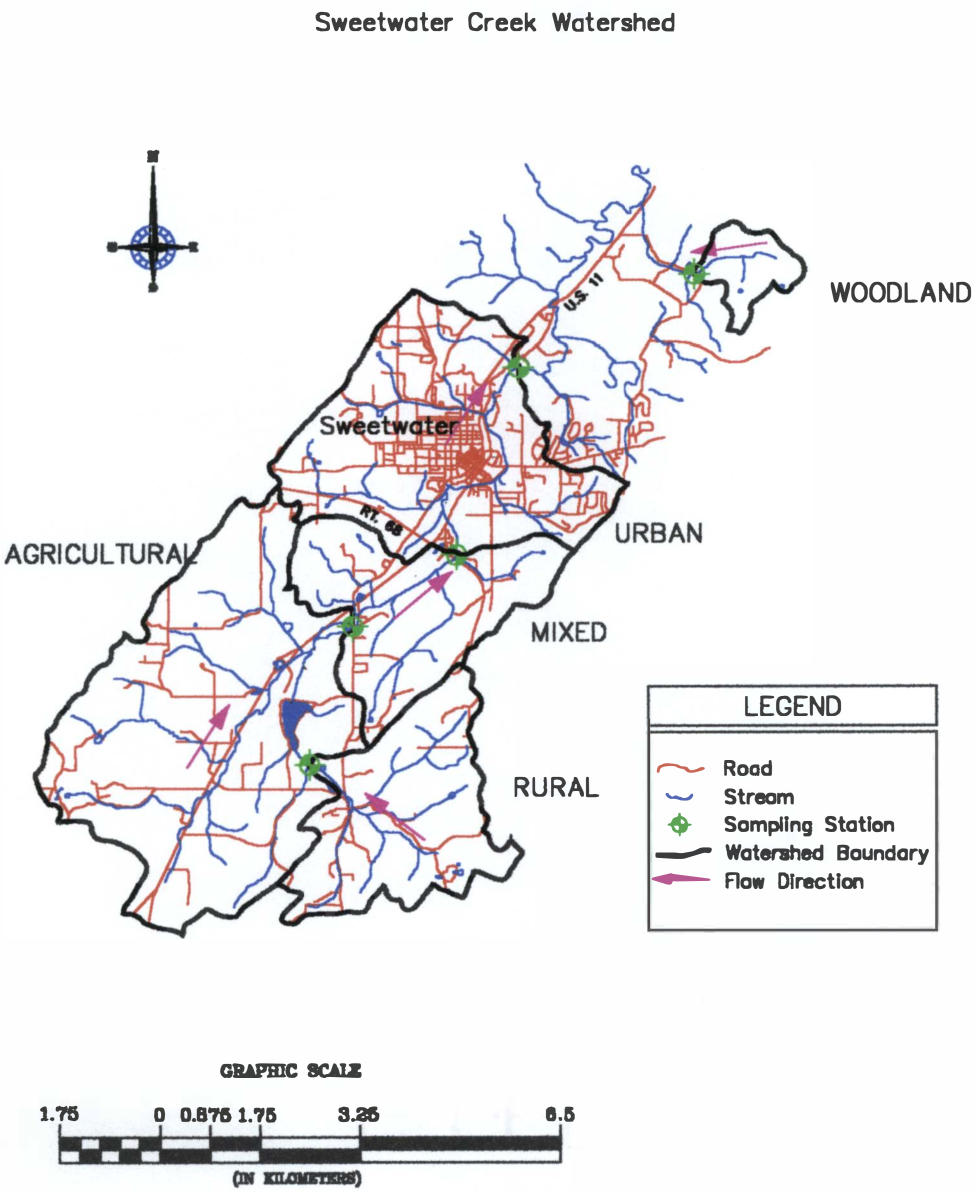

Figure 2: The site map displays pertinent watershed features and boundaries.

watershed and nutrients are found to be a problem with another, which provides the most impact? This question is a difficult one to answer. While nutrients may cause more harm to the entire ecosystem through eutrophication, algae blooms, and similar events, heavy metals may only be dangerous to bottom feeding fish since they could ingest the toxic levels of metals. In addition, the effects of some pollutants may have longer lasting effects than others. As a result, it is out of the scope of this project to define an overall water quality index or to develop extensive monitoring techniques for each constituent measured. However, this project provides a suitable foundation for such a tool, because in this project water quality was monitored and analyzed from a systemic standpoint.

Determining the primary pollutants from each of the sub-watersheds described above requires that the samples collected be analyzed routinely for all measurable constituents. Although this would provide the most complete information, the resources and manpower required to accomplish such a task would be phenomenal. As a result, constituents were selected in an effort to provide a degree of comparability between sub-watersheds, to work within the limitations of the testing laboratory, and to make the most efficient use of resources and manpower. These constituents were selected because they are typically used by researchers and regulatory agencies in order to get an idea of the status of the water quality. The constituents that were tested for in this project are listed in Chapter 4.

Chapter 4

Watershed Monitoring Strategy

A design to monitor water quality on a watershed basis may be elaborate or simple, depending on its goals. In the past, many monitoring strategies that were designed initially for point sources have been used in an attempt to monitor NPS pollution. In most cases, a monitoring strategy designed for point sources does not provide the information needed to adequately monitor NPS pollution because point sources usually provide a continuous or batch flow output. Therefore, monitoring the impacts from point sources is relatively straight forward in comparison to nonpoint sources. Nonpoint sources are more difficult to monitor because the pollutants do not emanate from a single, easily identifiable source. As a result, a more holistic approach such as monitoring NPS pollution on a watershed scale is needed to accurately define the NPS pollution occurring within the watershed.

The monitoring framework described in this chapter treats the stream as part of an overall system (the watershed) and is versatile enough to be implemented on watersheds of any size. It is designed to locate the portion of the watershed contributing most to water quality degradation. In this manner, systemic and localized pollutant contributions can be identified.

Foundation of Monitoring Framework

Typically monitoring strategies have not been as intensive enough, or encompassed a broad enough scale to track the variation in pollutant loading that occurs during normal flow, storm events, and from different land uses. A number of strategies exist that focus on the assessment of nonpoint source pollution.

Paired Watersheds

Arguably one of the most widely used strategies is the paired watershed design. This design utilizes two watersheds to determine whether best management practices are improving water quality. The two watersheds are "calibrated" using simple linear regression techniques based on flow or water quality concentration (or mass). In order for the calibration to be valid, there must be a significant relationship between the paired watersheds. The calibration period must be of a duration such that the data collected can be used to establish this relationship. In addition, residual errors must be smaller than the expected change due to the implementation of the best management practice. The two watersheds must be similar in size, slope, location, soils, and land use. Also, the land use must not change significantly prior to the evaluation so the watersheds are at steady state (EPA, 1993).

While this particular monitoring design can be useful in certain situations, there are a number of disadvantages:

1) It is usually not helpful in monitoring watersheds with water quality problems unless a suitable control watershed is located nearby.

2) It does not tend to work well for watersheds undergoing constant changes in land use, or watersheds that have had recent changes in land use.

3) There is no way to determine whether specific land uses or stream reaches within the watershed are contributing more or less to the NPS pollution.

Upstream/Downstream

Another approach commonly used in determining point source pollution is the upstream/downstream approach. In the upstream/downstream approach, samples are taken upstream of a point source and downstream of a point source. This allows the impact of the pollutant being discharged to be measured by subtracting the concentration, or mass, found in the upstream sample from the concentration, or mass, of the downstream sample (Spooner et al., 1985). A variation of this approach has been utilized in this monitoring framework in narrowing down problem areas in the overall watershed that act as "pseudo" point sources.

Steele et al. (1989) performed a study evaluating the impact of urban development on a small watershed in Denver, Colorado. The monitoring strategy was essentially an upstream/downstream approach that utilized automatic samplers to take samples at timed increments. Because samples were taken at timed intervals, the watershed hydrology was not really taken into account. As a result, an adequate correlation of pollutant loading during changing flow conditions could not be performed.

Because watershed hydrology is used as the foundation for the monitoring framework used on this project, the entire watershed is brought under examination rather than the stream itself. The foundation of the monitoring framework is based on the watershed characteristics that primarily contribute to NPS pollution such as rainfall, runoff, land use, and stream characteristics. This methodology provides a means to correlate the results obtained with hydrologic and watershed characteristics so that ways to reduce NPS pollution can be used on the direct cause of the problem.

One distinct advantage gained by basing the monitoring framework on watershed hydrology is that first flush effects can be characterized. First flush effects occur when pollutants that have collected on a land surface are carried by runoff during a storm event. A spike of pollutants is typically seen when the rate of change of runoff is the greatest. The largest rate of change of runoff will usually occur just before the peak storm flow occurs. If this is examined on a typical Type II storm hydrograph, the largest rate of change of runoff is at the steepest slope on the rising limb. Figure 3 depicts this first flush of pollutants during a storm event for a Type II storm runoff

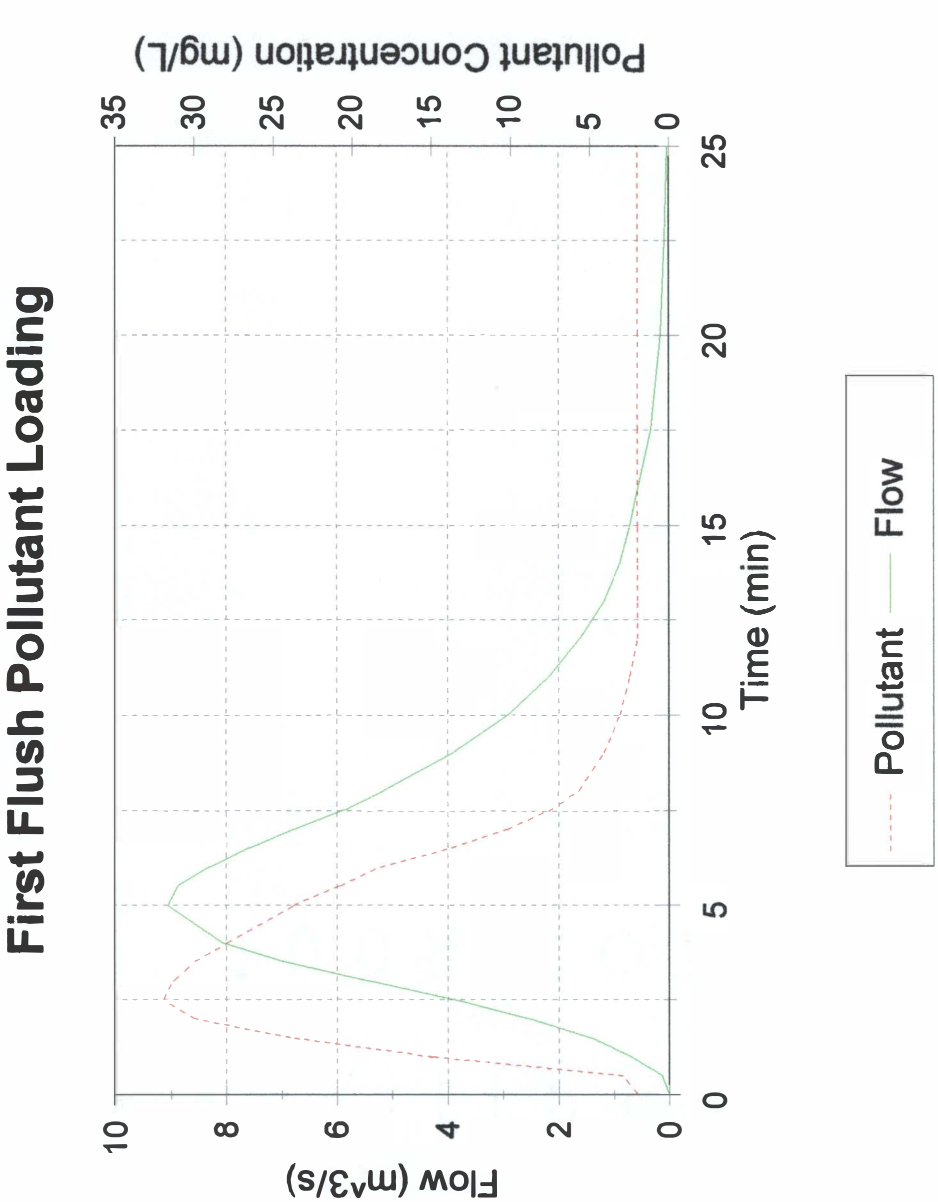

Figure 3: This graph depicts first flush pollutant loading during a Type II storm.

hydrograph. The specific shape of the runoff hydrograph is determined by watershed characteristics and the size/intensity of the storm.

Why are first flush affects important? By characterizing first flush effects, the majority of pollutants coming off a land use can be quantified with greater accuracy. The extent of water quality degradation from NPS can be estimated if first flush effects are measured. If extreme changes in pollutant levels are seen in the stream when there has been little or no rainfall, the source of the pollution is probably not driven by runoff.

NPS Monitoring Framework

Much of the NPS pollution that occurs may or may not be traced to specific areas within the watershed such as tributaries or discrete stream reaches. If land uses within the watershed are uniform, a NPS problem may be systemic. This framework is designed to monitor water quality problems whether they are systemic, or localized. Implementing the overall monitoring design is done in a series of steps which can be customized to encompass specific objectives or needs. Figure 4 displays a flowchart of the steps to be taken in establishing the NPS monitoring framework.

The monitoring framework presented here offers the following advantages:

- works with any type of storm or watershed
- does not require another similar watershed to be used as a control

Nonpoint Source Pollution Monitoring Framework Flowchart

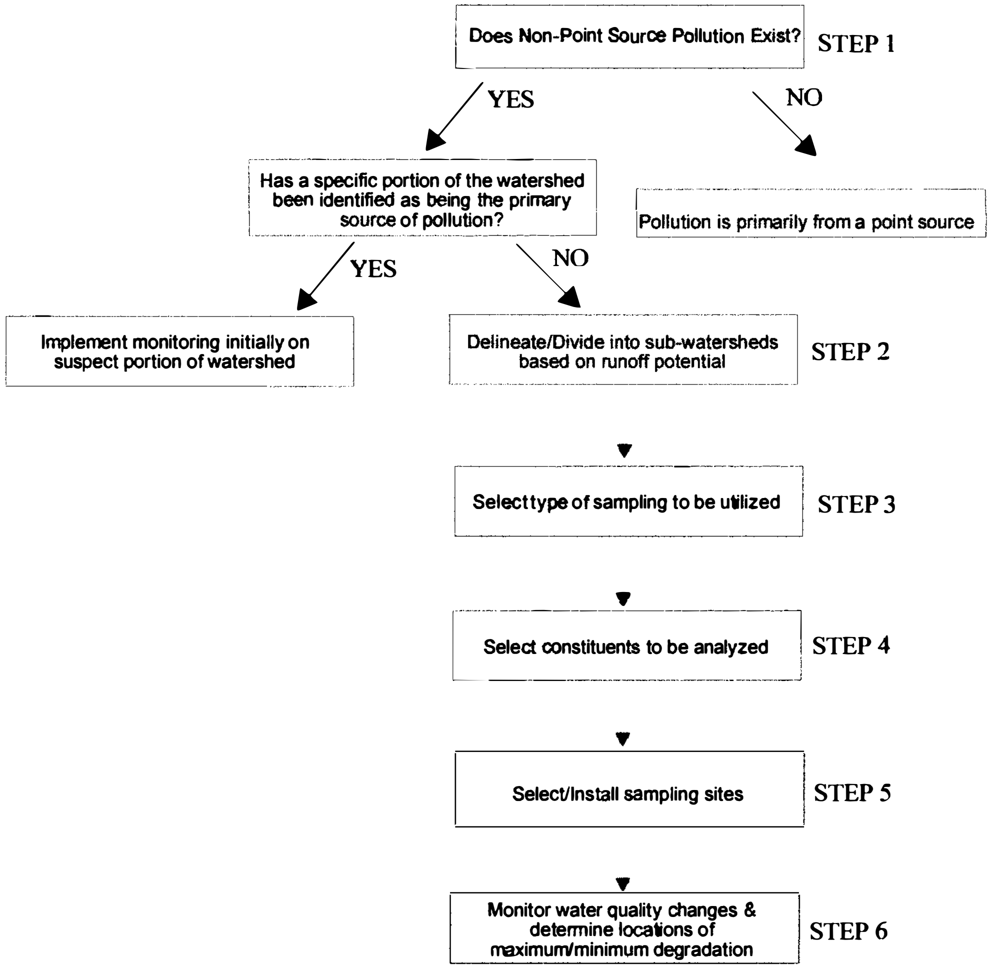

Figure 4: A flowchart is used to illustrate the monitoring framework implementation steps.

- utilizes watershed characteristics (e.g., land use, runoff potential) to designate sampling locations
- any desired sampling protocol(s) can be used

Step 1: Determine if a NPS problem exists.

Assuming that pollution is occurring within the watershed, the first step is the determination that the pollution is occurring from nonpoint sources. To do this, any potential point sources that may be causing significant pollution must be taken into consideration. A study must be performed to determine if there is a potential for pollution from point sources. Most point sources can be identified by walking the stream and locating pipes that could discharge into the stream. The landowner where the pipe is located should be identified to discover whether or not material is being discharged from the pipe. In addition, NPDES (National Pollution Discharge Elimination System) permits should be examined, since nearly all industrial and municipal discharges must be permitted. Additionally state government agencies will most likely have records of industries and municipalities that have discharge permits for a particular stream.

If there is still a question after these point source locations have been identified, initial grab sampling from the stream and flow measurements upstream and downstream of these point source locations along with examination of contaminant levels from point sources may give a good indication of whether or not water quality degradation is due to point or nonpoint sources. If the discharge is under the NPDES program the sample results should be available on public record. In addition, background water quality data from the stream (if it exists) will aid in confirming how much degradation, if any, has occurred over time. Once the existence of a NPS problem has been recognized, objectives must be set regarding how to monitor and reduce the NPS pollution. Despite the fact that NPS pollution may exist, actual implementation of the monitoring design will also hinge upon items such as the:

1) type of pollution and problems related to it,
2) resources available to implement and monitoring costs, and
3) public concern about the problem.

These three items will have a bearing on the urgency required in implementing a monitoring framework.

After the decision to implement the monitoring framework is reached, the level of complexity of the design depends on:

1) surface characteristics of the watershed,
2) land use, and
3) the specific contaminants that may be encountered (Buchanan et al., 1995).

The first two factors affect the mechanisms that cause NPS pollution, since they directly influence the hydrology. Sampling for contaminants that must be analyzed immediately, or within a short period of time, may result in monitoring schemes that are more complex. For example, testing water samples for fecal coliform bacteria requires that samples be tested within 6 hours. As a result, a separate monitoring scheme, such as grab sampling, may need to be established for constituents with a short holding time.

Step 2: Delineate and divide watershed into sub-watersheds.

The watershed for the stream in question must be delineated. This is best accomplished by acquiring topographic maps of the area (such as a United States Geologic Survey 7.5-minute quadrangle), roughing in the watershed boundaries, and then inspecting the entire watershed and finalizing the watershed boundaries based on visual observation and/or current aerial surveys.

The watershed should be divided into sub-watersheds based on watershed characteristics (e.g., land use, topography, etc.) and stream characteristics (e.g., flow). The objective is to divide the entire watershed so that potential areas of NPS pollution within the watershed can be isolated while minimizing equipment and sampling costs.

It may be necessary to sub-divide the watersheds further if large tracts of single land uses exist within the sub-watershed, or if specific areas are suspected of causing NPS pollution. If this approach is necessary, additional sampling sites may be needed above and below the suspect area to ensure the detection of pollutants from this specific area.

To delineate the sub-watersheds, the entire watershed should be examined by first traveling over the area to determine what land uses exist. Using a detailed map, the watershed is delineated based on the map contours and the experience gained from the watershed examination. With this done, the watershed should again be examined along with the delineated map to make corrections and to ensure that the divisions made on the map are fairly accurate.

Step 3: Select the type of sampling.

Typically, three sampling methods or variations of them are used: grab sampling, timed sampling, and flow proportional sampling. Grab sampling requires that someone travel to the sampling sites, take samples, and transport the samples to the laboratory. For grab sampling, the sampling frequency is typically not very intensive unless a specific event is being measured. If more than one grab sample is taken during a specific event, the sampling is typically performed in timed increments as flow proportional grab sampling can prove to be difficult.

Timed sampling takes samples at discrete time intervals by utilizing an automatic computer controlled sampler. This type of sampling is good in situations where pollutant concentration changes are slow, or when pollutant loading is not based on hydrology or flow characteristics.

Flow proportional sampling requires stream flow measurements. This is best explained with the following example:

> Samples are taken at discrete volumetric intervals; for example, after 18,927 L (5,000 gal) of water flows past the sampling site. The stream flow is used to calculate when this volumetric interval occurs. For example, using the 18,927-L volumetric interval at a flow of 3,785 L/min (1000 gpm) means that samples will be taken every 5 minutes (18,927/3,785 = 5 min) provided the flow remains constant. When the flow changes, samples will be taken more or less frequently.

Sampling in this manner means that more samples are obtained during storm events than during base flow since flow will be higher. This method is hydrologically based and provides good water quality information for runoff based NPS pollution.

Once sub-watersheds and the sampling method(s) have been identified it may be necessary to consider areal characteristics such as size, shape, and type of land surface. In addition, hydrologic characteristics such as stream flow, channel shape, slope, watershed response, rainfall and rainfall intensity are all important in determining the causal mechanisms for NPS pollution.

This information should be used to provide an assessment of which factors could contribute most to NPS pollution. Certain characteristics, or a combination of them, may provide insight in a specific situation as to where most NPS pollution is occurring within the watershed.

Step 4: Select the constituents to be analyzed.

In some situations only certain pollutants may need to be measured. However, analyzing a sweep of pollutants initially will help characterize the extent of the NPS pollution. If most of the pollution appears to be due to specific constituents, the protocol established for analyzing the pollutants (e.g., sample hold time) may dictate the type of sampling to be done.

Step 5: Select and install sampling sites.

With the watershed divided into sub-watersheds, the determination of which sub-watersheds to actually select for monitoring purposes must be made. It may be necessary to install sampling sites on all sub-watersheds depending on the reason for which the watershed is being monitored; however, some sampling sites may be eliminated by determining the pollution potential of the sub-watershed. This estimation technique can provide an idea of which sub-watersheds may be causing a majority of the pollution since a higher runoff potential indicates a greater chance that pollutants will be transported off-site. Consideration must also be given to factors such as localized BMP's, areas highly suspect for causing pollution (based on visual observation), man-made water conveyances, and similar non-natural items that could affect the runoff potential.

The following procedure should be used to estimate runoff potential:

1) Determine areas of sub-watersheds.

The area of each sub-watershed should be estimated from an accurate map or scaled aerial photo.

2) Determine C factors of sub-watersheds.

These factors should be calculated as weighted composites of the land uses that exist within the particular sub-watershed. A list of Rational Method C factors can be found in most hydrology or water engineering texts as well as the TR-55 Manual published by the NRCS.

3) Calculate the runoff potential by the following equation:

$$R_p = C \times A \qquad \text{[Eqn. 2]}$$

where R_p = runoff potential of the land use, ha

C = rational method runoff factor (unitless)

A = sub-watershed area, ha

The runoff potential provides an estimate of how much runoff could be expected from the sub-watershed assuming that the amount of runoff is constant for the entire watershed. This estimation technique is limited to smaller watersheds since the amount of runoff will begin to vary significantly for a given storm as the watershed area increases.

4) Rank the sub-watersheds having the largest runoff potential.

5) Select sampling locations at sub-watersheds with the highest runoff potential. The number of sampling locations will be dictated primarily by equipment availability and the project scope. Consideration should also be given to the security of the equipment, potential damage due to flooding, and protection of sample integrity.

Step 6: Monitor water quality changes and determine locations of maximum/minimum degradation.

Water quality monitoring should continue even after problems have been identified and also after solutions to the NPS problem have been implemented. This will ensure that additional problems will be discovered if they arise and that the implemented pollution controls continue to do their job. At this stage, the number of sampling sites can probably be decreased to one at the outlet of the entire watershed and one just above the affected sub-watershed (or the entire watershed if the problem is systemic).

Sample analysis can determine in which sub-watersheds most of the pollution is occurring or if the pollution is systemic. Nonpoint source pollution may be a problem only during sizable storm events when runoff that is generated becomes a large component of the overall stream flow.

If specific problem areas have been identified as contributing significant amounts of pollutants, the monitoring strategy must be narrowed to those particular areas. Sampling sites should be located upstream and downstream of suspect areas, or located using the flow based approach described in Step 2.

Chapter 5

Sampling System Development

The sampling system used for monitoring NPS pollution should take samples from the stream in a way that adequately characterizes fluctuations in pollutant concentrations. For regulatory compliance it is recognized that frequent, intensive sampling may not be necessary; however, more intensive sampling is typically necessary in performing water quality research, or during regulatory enforcement activities.

The sampling system used for a particular project must be determined based on the objectives of the project and the parameters to be analyzed. When taking samples two factors work against each other: cost effectiveness and sampling intensity. Cost effectiveness dictates that the least number of samples be taken because sample analysis is expensive. To determine the water quality impacts of each land use, sampling should be intensive enough to characterize the dynamic pollutant loading that usually occurs during runoff events. To reduce the overall number of samples to be analyzed and to gain the most useful information, sampling rates should be flow proportional to account for changing stream flow conditions.

The sampling system used to monitor NPS pollution must utilize watershed hydrology in specifying when samples are taken since NPS pollution is usually driven by runoff. As discussed in Chapter 4, it is desirable to take samples more intensively on the rising limb of the storm runoff hydrograph in order to catch first flush effects; with this method, more samples are taken at steeper hydrograph slopes, and sampling at baseflow is less intense. The hydrograph slope concept has been used in flood routing to study reservoir and spillway designs (Butler, 1982) but has been utilized very little, if at all, as a NPS pollution sampling technique.

By quantifying the amount of pollutants entering the stream during the first flush and for the remainder of the storm, the degree of water quality degradation due to land use within the watershed can be determined. Simultaneously, measures can be taken to reduce future NPS pollution by implementing runoff and erosion controls in areas of the watershed that are contributing to significant pollutant loading.

The sampling system for this project was developed to provide more control over when samples were taken in an effort to quantify more accurately pollutant loading in the stream during baseflow and storm events. A computer-controlled automatic sampler was used to take samples based on hydrograph slope. The determination of the hydrograph slope was based on specific watershed hydrologic characteristics. Grab samples were taken to monitor parameters with short holding times (< 7 days).

This sampling system allowed more detailed information on pollutant loading to be collected such as:

- the amount of pollutant loading occurring for a land use during normal flow and storm flow (especially during the rising limb of the hydrograph)
- when pollutant loading occurred during storm events
- the effect of runoff from a land use on stream water quality
- the residual effects of high pollutant loads on steam water quality

This method has been developed solely for the purpose of sampling NPS pollution. This type of sampling takes samples at irregular volumetric intervals based on the steepness of the hydrograph slope, while standard flow proportional sampling only takes samples at regular volumetric intervals. Timed sampling takes samples at discrete intervals of time. Figure 5 depicts how well each type of sampling characterizes a pollutant spike during a theoretical storm event. Notice that flow proportional sampling based on hydrograph slope takes nine samples over the storm event, while timed and flow proportional sampling take six and eight samples, respectively. More importantly, notice that sampling based on hydrograph slope collects more samples during the rising limb (60%) compared to timed sampling (33%) and flow proportional sampling (38%), resulting in a more accurate characterization of pollutant loading.

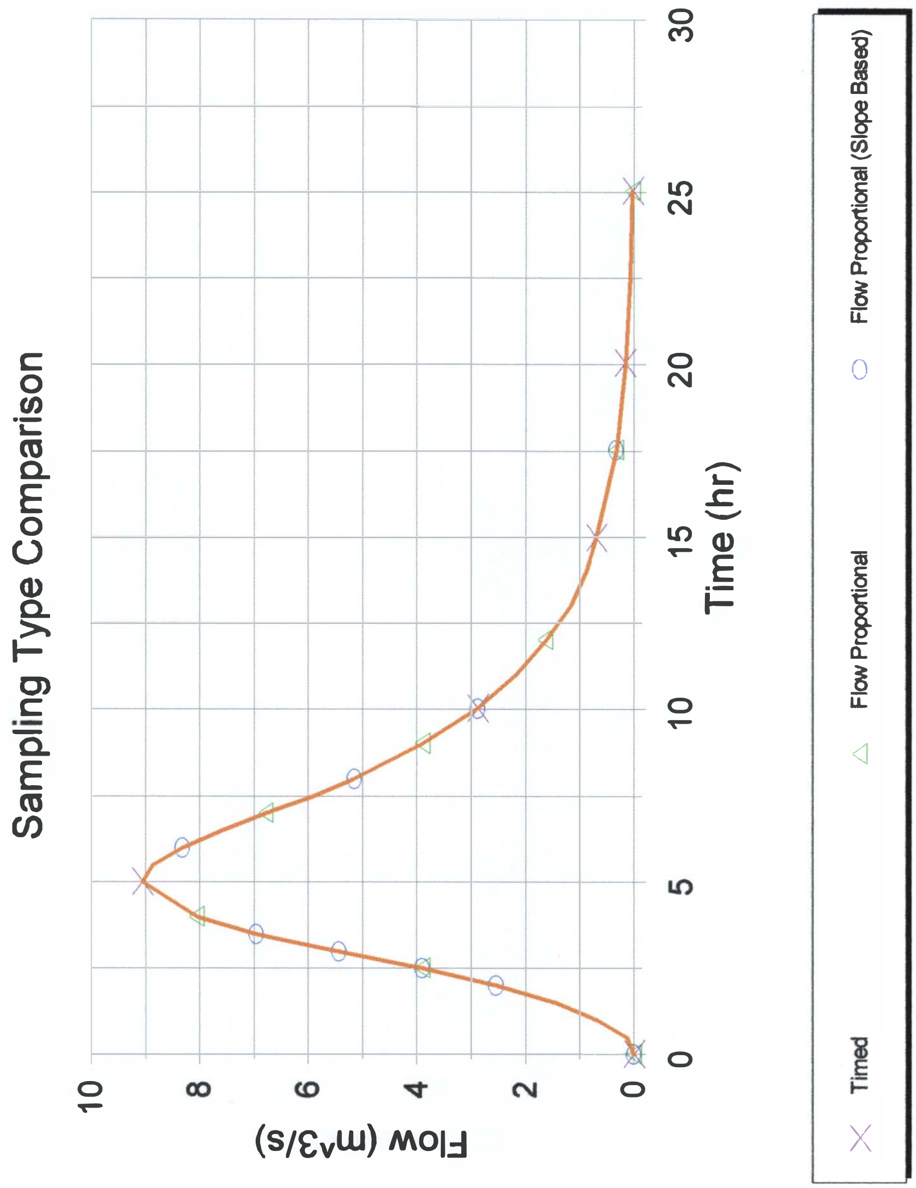

Figure 5: The sampling type used can determine how well the pollutant spike is characterized.

Procedure for Proportionally Sampling Based on Hydrograph Slope

The following step-by-step procedure was used to obtain the information needed to accomplish slope-based flow proportional sampling. Site specific watershed characteristics were needed to perform this type of sampling.

Step 1: Choose a design storm.

The first step was to choose an appropriate design storm for the watershed under study. Selection of the design storm was based on:

1) the maximum storm that could be accurately quantified in the field,

2) hydrologic limitations, and

3) the sampling equipment used.

The design storm selected was large enough to anticipate a significant flush of pollutants from a land use into the stream, yet small enough to be accurately quantifiable with field instrumentation. For example, it would have been pointless to specify a design storm that provided a stream depth of 1.5 m (5 ft) when the instrumentation used could only provide accurate flow measurements up to 1.2 m (4 ft) in depth. Hydrologic limitations also governed the design storm. A relationship could be established between depth and flow for any cross-section of a stream. If a design storm was chosen that overflowed the stream banks, the depth/flow relationship would not have held. Therefore, stream channel characteristics and how well flow could be measured during storm events had to be determined. The design storm had to be measurable but large enough to exceed a large percentage of the storms that will occur. The type of sampling equipment used in the field was also important, as the goal was to collect the maximum number of samples from a design storm without running out of sample bottles. Notice that this type of sampling works best with discrete sampling rather than composite sampling since specific portions of the baseflow and stormflow can be identified and evaluated separately.

For this project, the maximum depth that could be measured based on instrumentation and hydrologic limitation was approximately 1.2 m (4 ft, at the urban land use). An automated sampler was used that housed 24 bottles.

Step 2. Calculate time of concentration.

Time of concentration is the time it takes for runoff from the most remote point in the watershed to be seen at the watershed outlet. Time of concentration can be calculated using methods such as Kirpich's equation (Wanielista, 1990), Equation 3, which was developed in English units.

$$T_c = \frac{0.0078\ L_c^{0.77}}{S_c^{0.385}} + \left(\frac{2\ n\ L_o}{3\ \sqrt{S_o}}\right)^{0.467} \qquad [Eqn.3]$$

where T_c = time of concentration (min)

L_c = Length of channel (ft)

S_c = Slope of channel (ft/ft)

n = Roughness coefficient

L_o = Length of overland flow (ft)

S_o = Slope of overland flow (ft/ft)

This equation was used because it was developed in Tennessee for agricultural watersheds. All sub-watersheds in the study had a large agricultural or woodland component with the exception of the urban land use. The variables used for each sub-watershed and the resulting time of concentration calculated using Equation 3 are displayed in Table 3.

Step 3. Calculate the amount of rainfall for the chosen design storm.

The amount of rainfall is based on the location of the watershed in the U.S., the return period, and the duration. It is calculated using the Weiss equation (Schwab et al., 1993). The return period and duration of an event coupled with rainfall information from a number of design storms are used in the Weiss equation to interpolate the amount of rainfall for the design storm in question.

Table 3: Watershed parameters and time of concentration were calculated for each sub-watershed.

Land Use	L_c, m (ft)	S_c (m/m)	n	L_o, m (ft)	S_o (m/m)	T_c (min)
Rural	4,525.7 (14,520)	0.0103	0.8	241 (792)	0.0253	113
Mixed	9,012.3 (29,568)	0.0047	0.4	321.9 (1,056)	0.0047	246
Urban	13,599 (44,616)	0.0024	0.4	321.9 (1,056)	0.0047	352
Woodland	2,092 (6,864)	0.0364	0.8	161 (528)	0.114	49

Note: Abbreviations used are defined by Equation 3.

The duration of the event equates to the duration of rainfall excess and not necessarily the time of concentration calculated. In the design of this sampling system, equipment limitations dictated the size of the design storm used. The sampling system only holds a finite number of bottles; therefore, the maximum size storm that could be accurately sampled was a 2-year, 3-hour storm. The selection of a rainfall duration based on time of concentration would have resulted in not enough sample bottles during the design storm event. For a 2-year, 3 hour storm, the Weiss equation gave a rainfall amount of

2 in. for this storm. This equation was used to interpolate the rainfall amount from a number of figures and tables located in the reference text (Schwab et al., 1993).

Step 4. Determine the amount of runoff occurring for the watershed.

The SCS Curve number method was used for this calculation (Schwab et al., 1993). First, the storage was calculated by:

$$S = (25{,}400/N) - 254 \qquad \text{[Eqn. 4]}$$

where, S = max. potential difference between rainfall and runoff, starting at the time the storm begins (mm)

N = runoff curve number

Using the storage calculated above, the amount of runoff is given by:

$$Q = (I-0.2S)^2/(I+0.8S) \qquad \text{[Eqn. 5]}$$

where, Q = direct surface runoff (mm)

I = storm rainfall from Step 3 (mm)

S = max. potential difference between rainfall/runoff

Table 4 displays the calculated results from these equations for each sub-watershed.

Table 4: Curve number, S, and runoff amounts for each sub-watershed are summarized.

Land Use	Curve Number	S, mm (in.)	Runoff, mm (in.)
Rural	60	169 (6.67)	1.52 (0.060)
Mixed	65	137 (5.38)	9.04 (0.356)
Urban	65	137 (5.38)	9.04 (0.356)
Woodland	55	208 (8.18)	0.51 (0.020)

Step 5. Calculate the time to peak and the peak flow for the design storm.

These parameters were calculated using the SCS Synthetic Unit Hydrograph method (Wanielista, 1990). The time to peak flow was calculated using Equation 6.

$$t_p = (D/2) + 0.6*T_c \qquad \text{[Eqn. 6]}$$

where, t_p = time to peak flow (hr)

D = duration of the rainfall excess (hr)

T_c = time of concentration (hr)

The duration of the rainfall excess parameter, D, was equal to the duration of the design storm, in this case, 3 hours.

Peak flow (ft^3/s) was calculated using the following equation (developed for English units):

$$q_p = (484*A*R)/((D/2) + 0.6*T_c) \qquad \text{[Eqn. 7]}$$

where, A = watershed area (mi^2)

R = runoff amount (in.)

D = duration of rainfall excess (hr)

T_c = time of concentration (hr)

Table 5: Time to peak and peak flow have been calculated for each sub-watershed.

Land Use	Time To Peak (hr)	Peak Flow (m^3/s)	Peak Flow (cfs)
Rural	2.63	1.42	50.4
Mixed	4.0	8.21	290
Urban	5.0	9.06	320
Woodland	2.0	0.01	3.5

Step 6. Use dimensionless hydrograph ratios to generate a runoff hydrograph for the design storm.

Dimensionless hydrograph ratios of a Type II storm were used to generate the theoretical design storm for each subwatershed. The time to peak flow and peak flow values calculated in Step 5 were multiplied by the ratios to form the runoff hydrograph. When appropriate, dimensionless hydrograph ratios for Type I and Type III storms should be used.

Step 7. Calculate dimensionless hydrograph slopes for the design storm.

Dimensionless hydrograph slopes were found by multiplying the ratio of flow change during a specific time interval by the time to peak flow and peak flow values, using the following equation:

$$\text{SLOPE} = |(T_{peak}/Q_{peak})*(dQ/dT)| \qquad \text{[Eqn. 8]}$$

Dimensionless hydrograph slopes ranged between 0.2 and 2 for this design storm.

Figure 6 displays a spreadsheet with the dimensionless hydrograph ratios and the resulting storm hydrograph and hydrograph slopes generated for the design storm for each of the subwatersheds.

Theoretical Storm Runoff Hydrographs Using Dimensionless Hydrograph Ratios

(for a 2-yr return period, 3-hr duration storm)

PROJECT/LOCATION: Sweetwater Project (Sweetwater, TN)

Dimensionless Hydrograph Ratios (Wanielista, 1990)		**RURAL** *Tp = 2.63 hr; Qp = 51 cfs; Baseflow = 7 cfs*			**MIXED** *Tp = 3.96 hr; Qp = 290 cfs; Baseflow = 25 cfs*			**URBAN** *Tp = 5.01 hr; Qp = 320 cfs; Baseflow = 52 cfs*			**WOODLAND** *Tp = 2 hr; Qp = 3.5 cfs; Baseflow = 1.9 cfs*		
t/Tp	q/Qp	**Time** (hr)	**Flow** (ft^3/s)	**Slope**	**Time** (hr)	**Flow** (ft^3/s)	**Slope**	**Time** (hr)	**Flow** (ft^3/s)	**Slope**	**Time** (hr)	**Flow** (ft^3/s)	**Slope**
0	0	0.00	0.0		0.00	0		0.00	0		0.00	0.00	
0.1	0.015	0.26	0.8	0.150	0.40	4	0.150	0.50	5	0.150	0.20	0.05	0.150
0.2	0.075	0.53	3.8	0.600	0.79	22	0.600	1.00	24	0.600	0.40	0.26	0.600
0.3	0.16	0.79	8.2	0.850	1.19	46	0.850	1.50	51	0.850	0.60	0.56	0.850
0.4	0.28	1.05	14.3	1.200	1.58	81	1.200	2.00	90	1.200	0.80	0.98	1.200
0.5	0.43	1.32	21.9	1.500	1.98	125	1.500	2.51	138	1.500	1.00	1.51	1.500
0.6	0.6	1.58	30.6	1.700	2.38	174	1.700	3.01	192	1.700	1.20	2.10	1.700
0.7	0.77	1.84	39.3	1.700	2.77	223	1.700	3.51	246	1.700	1.40	2.70	1.700
0.8	0.89	2.10	45.4	1.200	3.17	258	1.200	4.01	285	1.200	1.60	3.12	1.200
1	1	2.63	51.0	0.550	3.96	290	0.550	5.01	320	0.550	2.00	3.50	0.550
1.1	0.98	2.89	50.0	0.200	4.36	284	0.200	5.51	314	0.200	2.20	3.43	0.200
1.2	0.92	3.16	46.9	0.600	4.75	267	0.600	6.01	294	0.600	2.40	3.22	0.600
1.3	0.84	3.42	42.8	0.800	5.15	244	0.800	6.51	269	0.800	2.60	2.94	0.800
1.4	0.75	3.68	38.3	0.900	5.54	218	0.900	7.01	240	0.900	2.80	2.63	0.900
1.5	0.65	3.95	33.2	1.000	5.94	189	1.000	7.52	208	1.000	3.00	2.28	1.000
1.6	0.57	4.21	29.1	0.800	6.34	165	0.800	8.02	182	0.800	3.20	2.00	0.800
1.8	0.43	4.73	21.9	0.700	7.13	125	0.700	9.02	138	0.700	3.60	1.51	0.700
2	0.32	5.26	16.3	0.550	7.92	93	0.550	10.02	102	0.550	4.00	1.12	0.550
2.2	0.24	5.79	12.2	0.400	8.71	70	0.400	11.02	77	0.400	4.40	0.84	0.400
2.4	0.18	6.31	9.2	0.300	9.50	52	0.300	12.02	58	0.300	4.80	0.63	0.300
2.6	0.13	6.84	6.6	0.250	10.30	38	0.250	13.03	42	0.250	5.20	0.46	0.250
2.8	0.098	7.36	5.0	0.160	11.09	28	0.160	14.03	31	0.160	5.60	0.34	0.160
3.5	0.036	9.21	1.8	0.089	13.86	10	0.089	17.54	12	0.089	7.00	0.13	0.089
4	0.018	10.52	0.9	0.036	15.84	5	0.036	20.04	6	0.036	8.00	0.06	0.036
4.5	0.009	11.84	0.5	0.018	17.82	3	0.018	22.55	3	0.018	9.00	0.03	0.018
5	0.004	13.15	0.2	0.010	19.80	1	0.010	25.05	1	0.010	10.00	0.01	0.010

Dimensionless Slope Eqn.: SLOPE = (Tp/Qp)*(dQ/dT)

Figure 6: Land use hydrographs were calculated using dimensionless hydrograph ratios.

Step 8. Select base flow sampling rate and maximum sampling rate.

From streamflow measurements, the base flow for each stream was determined as was how often samples were to be taken when no storm event was occurring. This depended on the hydrologic response of the watershed, point sources entering the stream, and land uses within the watershed. If the watershed was very responsive (i.e., a large percentage of the stream flow was due to runoff) fewer samples were taken at base flow so that more were taken during storm events. However, if point sources existed, more samples were needed at base flow. It was usually desirable to take as many samples as possible, even at base flow. It was also desirable to modify the base flow sampling rate depending on variability in pollutant concentration during non-storm events; this depended on characteristics such as watershed size, groundwater interaction, point sources, agricultural/construction activity, and seasonal components.

The maximum sampling interval typically depends on how fast the sampler can operate. For the ISCO samplers, a sample can be taken every 1 to 2 minutes, depending on rinse cycles and tubing length. The maximum and minimum sampling intervals set for this project were 2 minutes and 6 hours, respectively. A maximum rate of one sample every 2 minutes was set based on the minimum rinse cycle time and the tubing length required at each sampling station. A minimum rate of one sample every 6 hours upon initial sampling proved to be adequate in detecting small changes in pollutant concentrations during baseflow. There appeared to be no significant factors that warranted a shorter sampling interval at baseflow.

Step 9. Determine a setpoint volume.

A setpoint volume was defined as the amount of water that must pass by the sampling site before the automated sampler was triggered. The actual volume was calculated by multiplying the base flow sampling rate by the base flow, as seen in Equation 9.

$$\text{SETPOINT VOLUME} = \text{SAMPLE RATE}_{\text{BASE}} * \text{FLOW}_{\text{BASE}} \qquad \text{[Eqn. 9]}$$

The setpoint volume was used to trigger the sampler. The volume of water flowing past the sampling site was tabulated and the computer activated when the setpoint volume was reached. The computer used a stage-discharge curve to calculate flow and to change this to a volume. The stage-discharge curve was an equation that had been fitted to streamflow measurements taken at various flow stages at the stream cross-section where the sampling was performed. The setpoint volume was obtained by determining when there was no significant change in hydrograph slope over a specific time.

Step 10. Use the dimensionless hydrograph slope from Step 7 to calculate a variable setpoint volume.

The hydrograph slope was determined in the field by measuring the streamflow at frequent, discrete time intervals, and inserting these values into Equation 8 in Step 7. Streamflow was estimated by the computer via a pre-determined stage/discharge relationship. This relationship was found by taking flow and depth measurements at an established cross-section in the stream. At least 4 to 5 flow/depth measurements were taken at varying flows. A wide range of measurements were taken to ensure an accurate stage/discharge relationship. The cross-section that was utilized was at the same location where sampling took place. When enough measurements were taken, a plot was made of flow versus depth and a regression curve was generated through the points. These flow measurements were taken using a Marsh McBirney velocimeter. The procedure for making streamflow measurements using this device is provided in Appendix A. The subsequent equation was used by the computer to convert depth to flow. The computer calculated streamflow and information was used to calculate the hydrograph slope.

Figures 7 - 10 display the stage/discharge curves and equations for each subwatershed based on in-field measurements. Repeated flow measurements in the field showed that

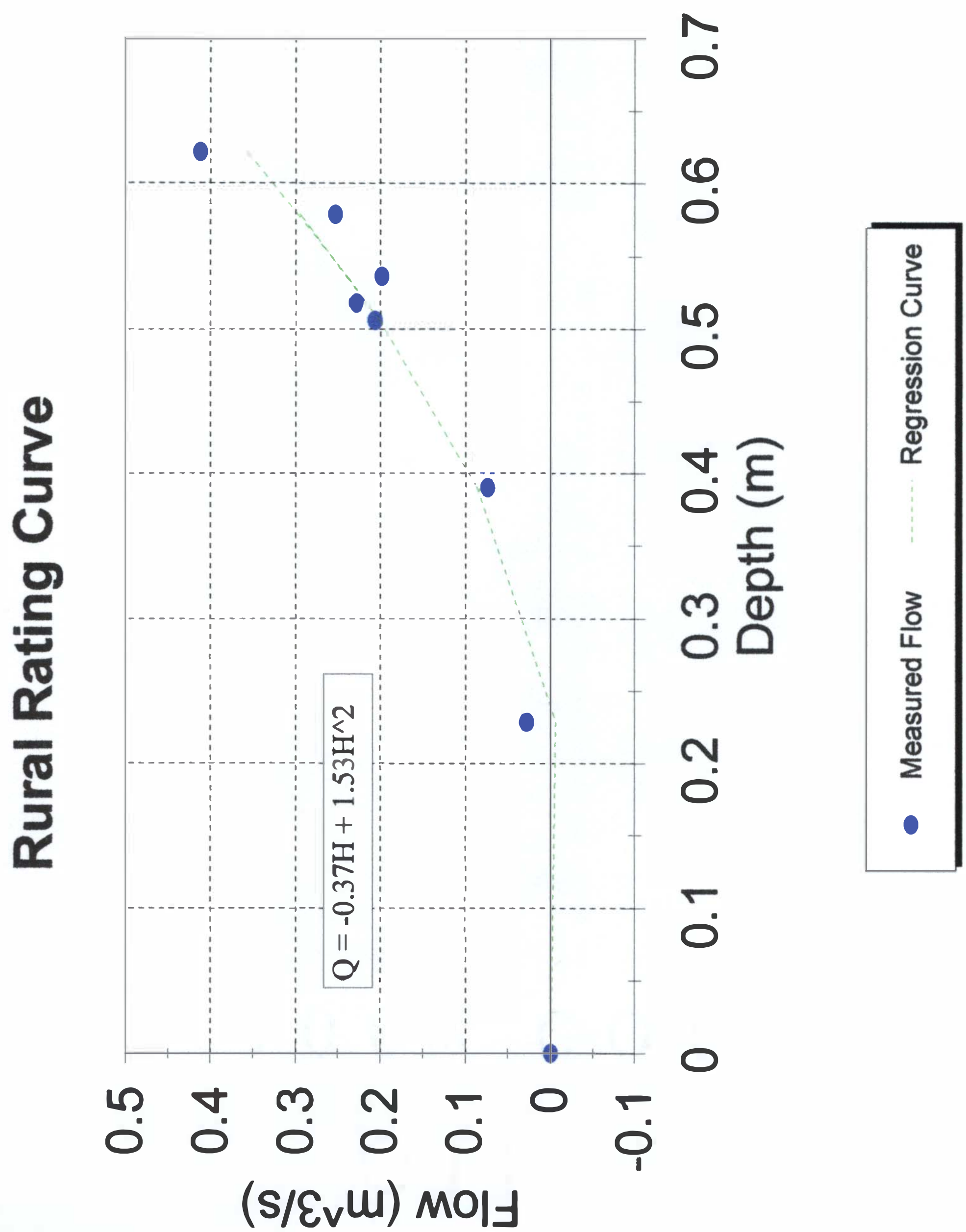

Figure 7: The stage/discharge curve that was developed for the rural land use.

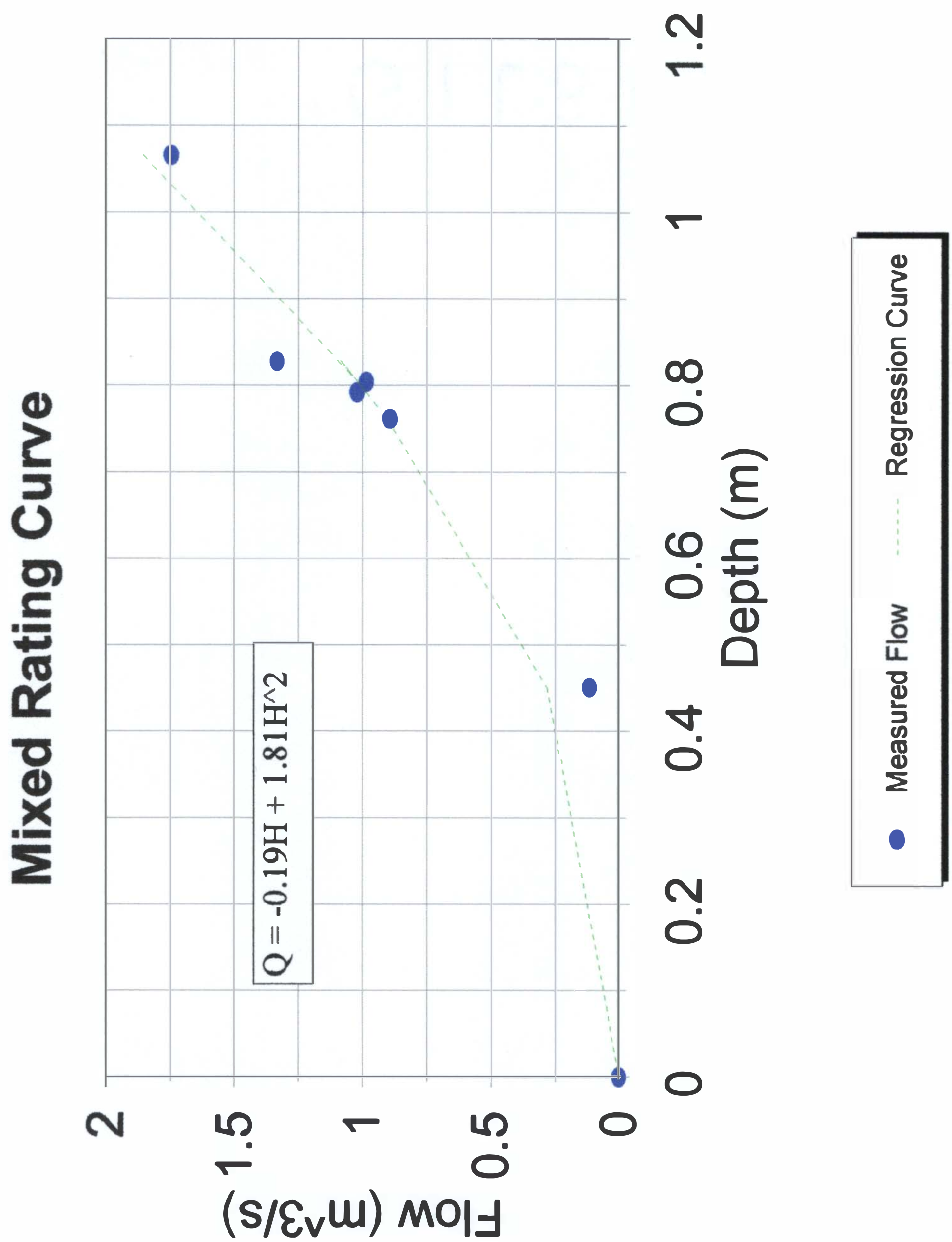

Figure 8: The stage/discharge curve that was developed for the mixed land use.

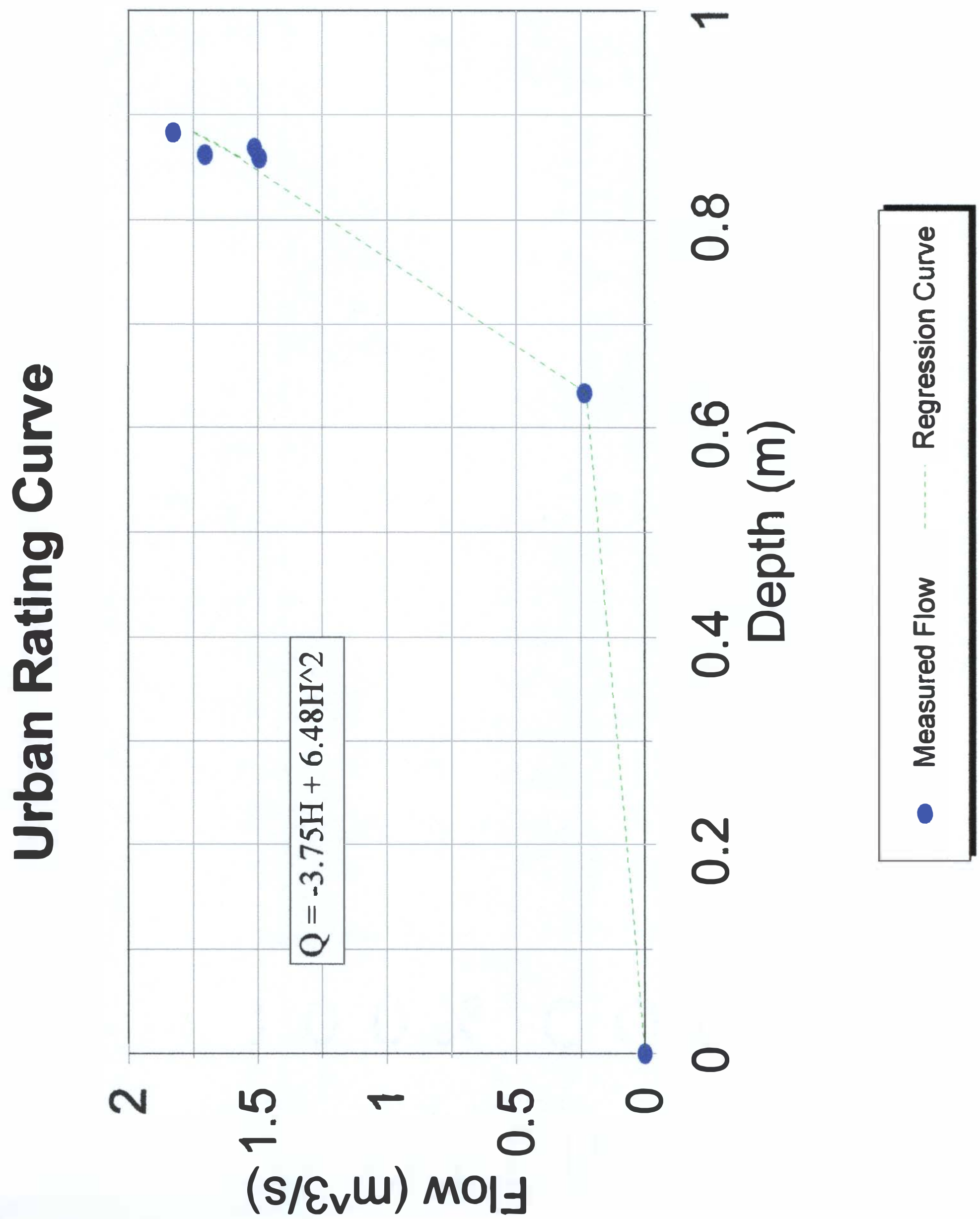

Figure 9: The stage/discharge curve that was developed for the urban land use.

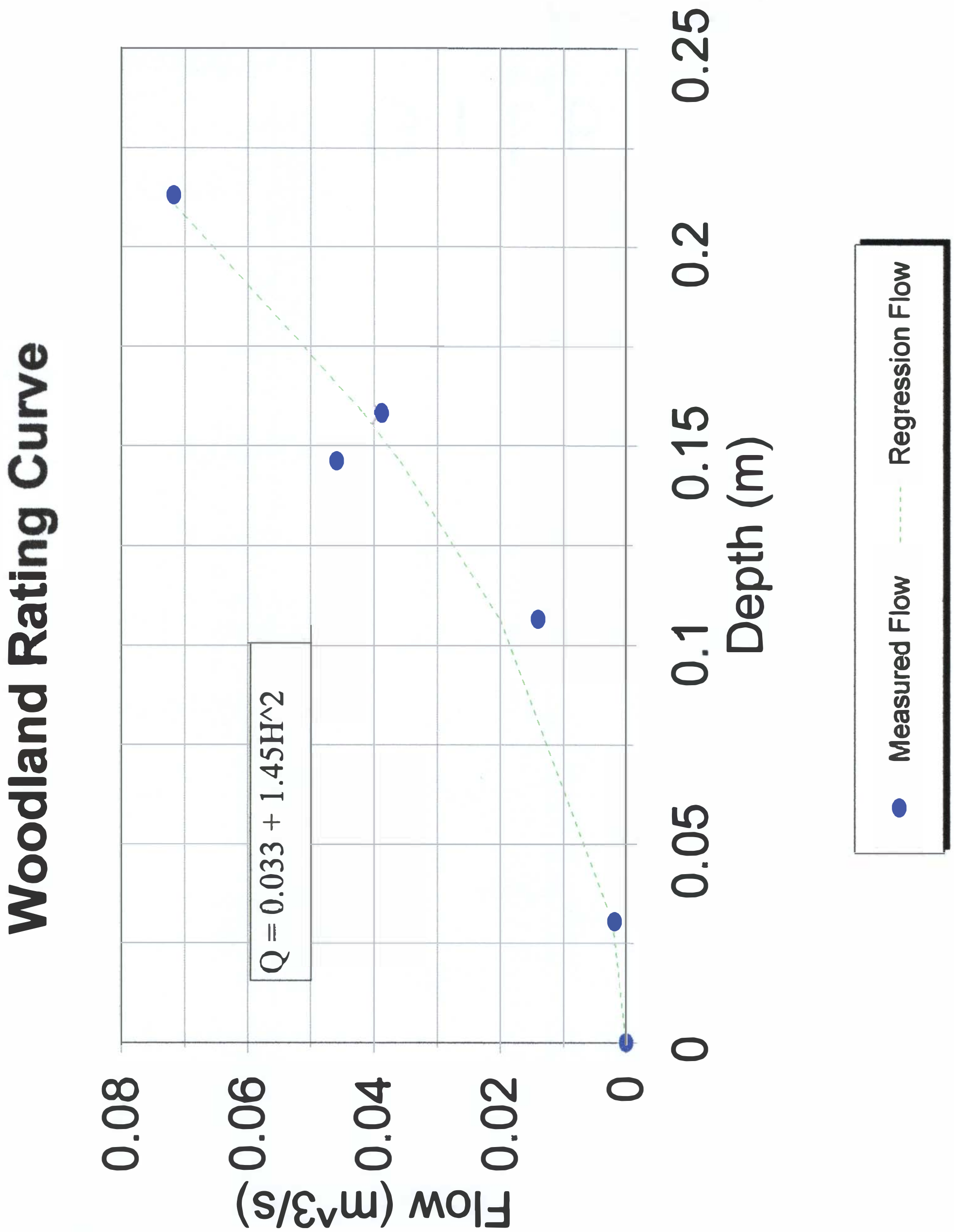

Figure 10: The stage/discharge curve that was developed for the woodland land use.

the resulting equations provided accuracies within 5 to 10% except when flows exceeded the highest flow measured.

A multiplier was used to vary the setpoint volume. In other words, as the hydrograph slope increased the setpoint volume became smaller so that more samples were taken. This was done by interpolating a sampling rate, y, at the calculated dimensionless slope. The equation is:

$$y = [(\text{Slope} - 0.2)\,(2 - 3600)/(2 - 0.2)] + 3600 \qquad \text{[Eqn. 10]}$$

which is solved for y to get the sampling rate. Equation 10 is a linear interpolation between the minimum and maximum sampling intervals (2 min and 3,600 min, see Step 8) and the minimum and maximum dimensionless hydrograph slopes (0.2 and 2, see Figure 5). The slope was then divided by the baseflow sampling rate to get the setpoint volume multiplier. Figure 11 displays graphically how the sampling rate was obtained by interpolation using a dimensionless slope of 1.2 as an example.

It is hoped that this type of sampling will prove more effective than either timed or standard flow proportional sampling, in that more samples are taken at steeper slopes where it is thought that the majority of pollutant loading occurring during a storm event. Research has shown, though, that exactly when maximum pollutant loading

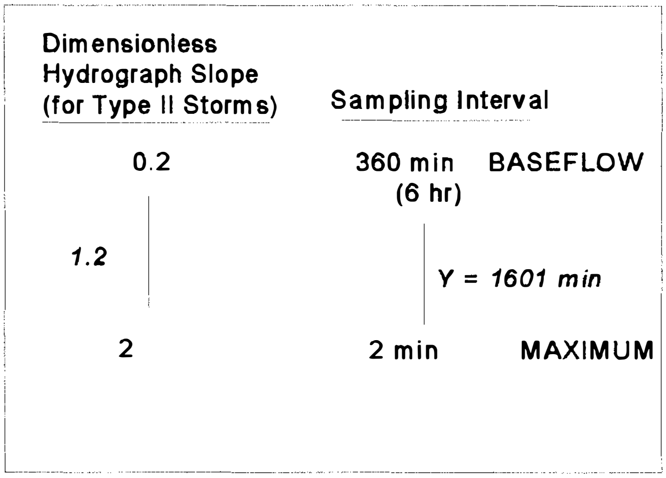

Figure 11: The sampling interval was interpolated from the dimensionless slope.

occurs was not clear. Some research implies that the above assumption is true; however, at this time no clear relationship has been established between pollutant concentration and flow (Claridge, 1975).

Equipment

Each sampling site was equipped with an automated sampler coupled to a programmable single board microcomputer. The computer monitored depth via a depth sensing device called a Tennessee Fluid Level Indicator (TFLI) developed by the University of Tennessee Agricultural and Biosystems Engineering Department. The computer calculated flow based on the depth measured via the stage/discharge equation for each subwatershed. Once the appropriate setpoint volume was reached the automated sampler was triggered by the computer. At some sites, rain gages were been installed and were linked to the computer to monitor rainfall. Rain gages were installed late in the project, so very little data was been collected on rainfall amounts. Data were downloaded and samples were taken on a weekly basis. Power requirements for each site were met with 12-V deep-cycle marine batteries.

Automated Sampler

ISCO 3700 automated samplers were used at all sites except the woodland land use. These samplers can be programmed to take timed samples or to be triggered by pulses for flow proportional sampling. Twenty-four, 350-ml bottles were housed within the sampler to hold samples. Samples were multiplexed such that five samples were placed in each bottle. This was chosen because it offered the best sampling resolution for the design storm without running out of bottles before the storm ended. For example, if the sampler was sampling at the minimum interval (which was roughly 2 minutes per sample) each bottle represented about a 10-minute period during the storm. A 60-ml sample size was used to account for sampling variation so the bottles did not overflow. ISCO sampling accuracy was within 10% of the programmed sample size (ISCO, 1991). Samples were retrieved via a peristaltic pump which reduced sample contamination and facilitated accuracy by purging the line with air before sampling.

A Manning automated sampler was used at the woodland site. This device was an older model but was somewhat similar to the ISCO samplers. It utilized a chamber to measure sample size, which increased the chance for sample cross-contamination. The Manning also held 24 bottles and ten samples were placed into each bottle. This sampler was not computer controlled like the ISCOs, but was operated on a timed sampling scheme because it was thought that there would be less variation in water quality at this site. The Manning sampler was used because no additional samplers were available for the project.

Single Board Microcomputer

An Octagon 5081 microcontroller was used to read depth from the depth sensor, to calculate flow, and to trigger the ISCO samplers. The microcontroller was selected over other devices (such as dataloggers) because of the capability to control other devices easily and inexpensively. The microcontroller had a simplistic programming language called CAMBASIC, which is a derivative of the BASIC programming language. Programs were stored in the computer's EEPROM and the computer was capable of monitoring or controlling both analog and digital devices. The computer was programmed to store time, date, depth, flow, and rainfall information. However, the microcontroller's ruggedness and durability in the field proved to be a problem. As a result, these controllers were replaced with a controller more suited to the harsh environment at the end of the project.

Depth Sensor - Tennessee Fluid Level Indicator

The depth sensing device used for this project was developed by the University of Tennessee Agricultural and Biosystems Engineering Department to provide an economical method for obtaining accurate depth measurements (Yoder et al., 1999). The Tennessee Fluid Level Indicator or TFLI is essentially a weighted tube placed in a stilling well. The tube hangs from a load cell which measures force. In a body of water, when the depth rises or falls, the tube becomes more or less buoyant depending on depth. This in turn decreases or increases the weight of the tube and the load cell monitors these changes. The signal from the load cell is boosted with an amplifier and sent to the single board computer. A more detailed description of the TFLI can be found in Appendix B.

Overall Set-up

It was important to locate the sampler at a location on the stream bank that protected it as much as possible from flooding, vandals, and other unforseen hazards. Both the battery and computer were suspended from 1.8-m (6-ft) steel fenceposts for protection.

Support brackets kept the battery and computer about 0.9 m (3 ft) off the ground. A steel cable and chain were used to secure the sampler and battery to the fence posts.

Devices were wired to minimize power consumption. Relays were used with the computer when controlling the sampler and TFLI to keep the devices from being excited constantly and to reduce power drain on the battery. Power was supplied to the sampler and computer on separate circuits to reduce electrical noise and interference. Fuses protected the computer from wiring to the battery backwards and voltage regulators reduce the chance of damage due to voltage spikes. Where possible, connections were soldered to reduce electrical noise and the chance of disconnection.

Computer Programming

The program developed for the Sweetwater Creek project controlled and monitored all devices and provided data storage. A separate program was used to retrieve data from the computer. The programmable controller provided a fair amount of versatility; however, problems were encountered with limited storage of data.

The computer program used at each site can be found in Appendix C. The primary components of the program are:

1) conversion of voltage to stream depth (TFLI Calibration Curve),

2) conversion of depth to flow (Stage-Discharge Curve), and

3) computation of hydrograph slope and sampler triggered.

Voltage readings from the load cell of the TFLI were converted to corresponding depths using the equation determined from calibration. The TFLI calibration curve has the form of a simple linear equation:

$$H = m*V + b \qquad \text{[Eqn. 11]}$$

where, H = depth

m = slope of line

V = voltage measured from load cell

b = offset

Depth readings were averaged over a period of time to reduce variation due to random noise. This was important since small variations in depth could result in large flow fluctuations.

The equation derived from the stage/discharge relationship for each subwatershed (Figures 6 - 9) was entered into the computer. Computation of the hydrograph slope and sampler activation was performed via the procedures and equations outlined in this chapter.

Chapter 6

Results and Discussion

Primary efforts for the duration of this project were centered on the development of a monitoring strategy and design of a sampling system to monitor NPS pollution. In addition, the strategy and sampling system developed were applied to the Sweetwater Creek watershed to test the system for determining water quality changes due to land use. Monitoring was performed to examine the primary pollutants from each land use within the watershed. In order to accomplish these objectives, special emphasis was placed on ensuring that the monitoring strategy and sampling system had the ability to accurately identify the runoff component in the candidate stream so that NPS impacts from land uses could be studied with measurable results.

Monitoring Strategy

Effectiveness of Monitoring Strategy

The monitoring strategy used for this project was developed to effectively monitor water quality impacts from nonpoint sources. This strategy is discussed in detail in Chapter 4.

In general, the monitoring strategy could be adapted for any size watershed where monitoring NPS pollution is required. The structure of the strategy provides a loose yet decisive framework that allows flexibility while providing an established procedure to follow. The structure of this monitoring strategy provides a high level of efficiency and effectiveness in comparison to the paired watershed approach or capital intensive strategies that require a substantial amount of hardware and labor to implement. This strategy, if implemented correctly, should provide a strong indication of exact locations within a particular watershed that are causing a significant portion of the NPS pollution.

For this project, the conceptual monitoring strategy was modified slightly since the selected watershed had not been identified as having a nonpoint source pollution problem. The criteria for selecting this watershed were presented in Chapter 3. In addition, the last step of the strategy, monitoring changes after steps have been taken to reduce pollution, has not yet been fully realized since data is still being collected.

This strategy was developed for this project to fit the holistic monitoring approach described in Chapter 1. It is stressed that one of the most important aspects of this strategy is the selection of the type of sampling used since the quality of the results obtained hinge largely on this component. As a result, a significant amount of time should be spent developing an effective sampling system or regime that is based on watershed characteristics.

Applying this strategy to the Sweetwater Creek watershed has provided a sound decision making procedure to research the performance of the sampling system that was developed and to monitor water quality from varying land uses. As with any strategy, the usefulness and success is only as good as the personnel and tools used in the evaluation of the watershed. Educated and informed decisions must be made at each step of the strategy to reach the desired goal.

Functionality and Limitations of Monitoring Strategy

The strategy utilized for this project was been developed for most types of NPS pollution monitoring projects, such as:

1) NPS monitoring for water quality improvement/degradation studies (e.g., Sweetwater Creek)
2) Regulatory watershed monitoring for compliance, BMP effectiveness, etc.
3) Storm and base flow monitoring to evaluate stormwater controls and to provide technical data for generating watershed pollution prevention plans.

As regulatory agencies continue to tighten water quality rules, a greater need will be recognized for a consistent, standardized methodology for evaluating NPS pollution. This strategy provides the methodology and allows flexibility; however, there are limitations. The strategy is not well suited to watersheds with significant point source loading. In order to incorporate point source loading, a subroutine for the strategy would need to be developed to address pollutant loading that does not use runoff as its transport mechanism.

If utilized on watersheds with complex land use patterns this strategy may tend to attenuate the pollution potential. This would occur in situations where the watershed is divided based on runoff potential. In watersheds with complex land use patterns a weighted runoff potential would be used; areas with significant pollutant loading may be overlooked due to averaging. As a result, it is suggested that interpretations be made for such areas and adjustments be made as necessary to effectively monitor such problem areas.

More detailed evaluation techniques may need to be implemented on watersheds with only one or two primary land uses. If these techniques are not implemented, the strategy may provide results that are difficult to evaluate. In this case it is suggested that monitoring be performed based on suspected areas of pollution, or that a detailed runoff potential analysis be performed.

Sampling System

Prototype Testing In Lab

The sampling system was tested in the laboratory under controlled conditions to ensure proper operation of the system. The main objective of the lab test was to ensure proper and accurate operation of the sampling system and to anticipate any potential problems that may occur in the field.

Lab facilities in the University of Tennessee Agricultural and Biosystems Engineering Department provided excellent control of variables that would be uncontrollable in the field. A concrete, rectangular raceway in the floor of the hydraulics lab was used for testing. Flow was provided via a hydrograph generator (Yoder et al., 1998) able to produce a range of flow from 0.2 L/s (3 gpm) to 16 L/s (250 gpm) at an accuracy of 1-2%. The hydrograph generator can simulate runoff events for a wide range of design storms. A concrete, in-floor stilling well connected to the concrete raceway was used for the installation of the depth sensor (TFLI). The sampler, computer, and power supply were located adjacent to the stilling well.

The hydrograph generator emptied into the concrete raceway approximately 457 cm (15 ft) from a triangular weir. The weir was utilized explicitly to create a measurable depth in the raceway rather than for flow measurement since flow was already being measured via the hydrograph generator.

The hydrograph generator controlled flow by receiving input from a data file generated by the user. The 2-year, 3-hour design storm used for the actual Sweetwater Creek watershed was scaled down to a duration of one hour to be used in the lab. Two runs were performed to establish system repeatability and to quantify accuracy.

A primary focus of the lab test was to ensure that the proper hydrograph slope and setpoint volume were calculated in order to trigger the sampler at the appropriate flow intervals. First run results revealed that the sampler was being triggered often but not at the anticipated flow intervals (Figure 12). Programming errors were noticed in the first run and were corrected. The second run was more successful, with 60 % of the samples being taken during the rising limb of the hydrograph (Figure 13). The performance of the sampler for this run compared well with theoretical estimates for both storm and base flow. These results confirmed that the sampling system had the ability to quantify first flush pollutant loading during significant runoff events. The program logic for the sampling system assumed that increases in pollutant loading occur at times when flow is changed significantly.

Sampling System Field Testing

Data Collection

Upon field installation of the sampling system, a number of significant problems were encountered that affected data collection. The reliability of the single board computers

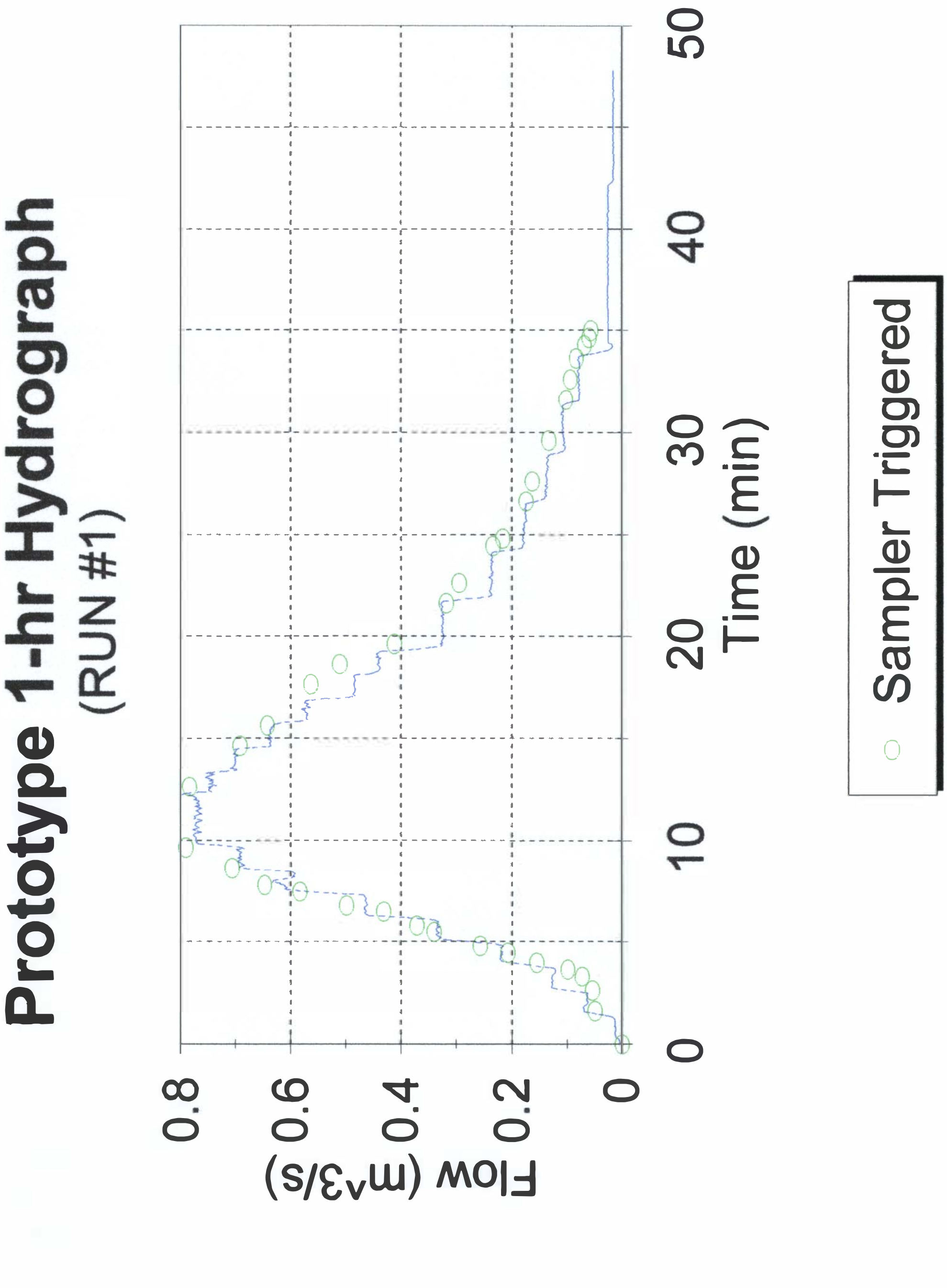

Figure 12: First run prototype testing results are shown.

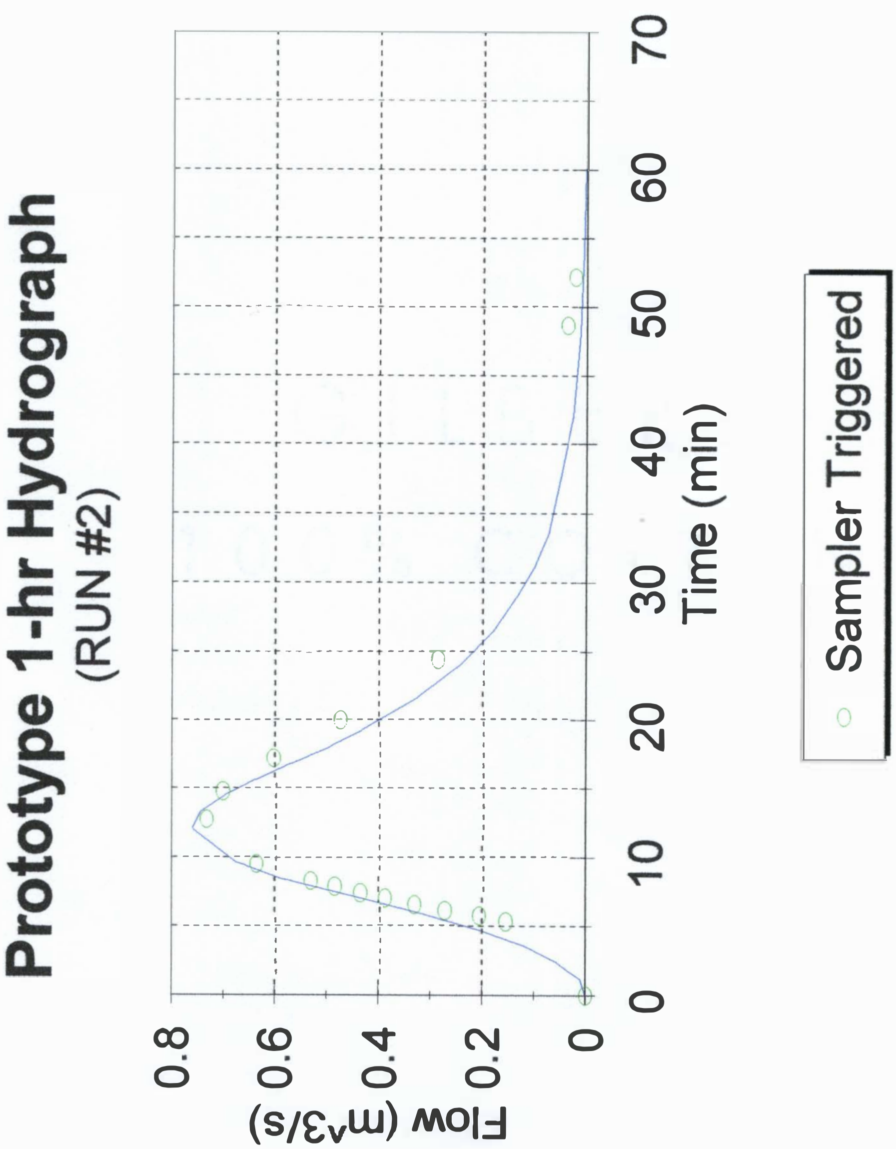

Figure 13: Second run prototype testing results are shown.

was the largest factor affecting system operation in the field. An extensive amount of time was spent troubleshooting the system in the field to get it operating as it had during the lab testing. Of the factors affecting system performance in the field, temperature and humidity extremes played the largest roles in reducing system reliability despite precautions. These problems resulted in a number of errors:

1) Loss of flow data
2) Sampling at incorrect times, or insufficient sampling during storm events
3) System shut-down

The data collected from storm events typically had gaps due to one or more samplers operating incorrectly in the field. As a result of these problems, there were too many gaps in storm event data to warrant a detailed analysis of storm data. The selection of a hardier computer control system designed for rugged conditions (e.g., a datalogger or PLC) should have been utilized and would have resulted in a vast improvement in field operation.

Constituents Tested

There are a multitude of constituents that could be tested in order to quantify water quality. Ultimately the selection of constituents to be tested is typically based on which parameters give the best indication of water quality for the least cost. In addition, factors such as availability of analytical equipment, sampling protocol, and whether or not it would be feasible to find the constituent in the stream should be considered. The constituents for this project were selected in the interest of maintaining sample integrity and reducing analysis cost while providing as much information as possible. In addition, these parameters are typically chosen for analysis by regulatory agencies because they have been historically recognized as some of the primary indicators of water quality.

Samples taken by the automated samplers allowed for water quality information to be obtained without requiring that someone take the samples by hand; however, sample integrity was compromised for some constituents such as fecal coliform bacteria and biochemical oxygen demand since they must be analyzed within a short period of time. This is because these parameters can change significantly over a short period of time; therefore, sample analysis must be expedited. For these kinds of constituents, grab samples were taken. Table 5 displays the list of constituents tested for grab and automated sampling.

Some samples (both grab and automated) were screened on a limited basis for certain metals. The constituents tested are typically found in runoff from most types of land uses.

Table 5: List of constituents tested from automated and grab samples.

Constituent Tested	Grab Samples	Automated Samples
Total Solids	✔	✔
Total Organic Carbon	✔	✔
Chloride	✔	✔
Nitrite	✔	✔
Nitrate	✔	✔
Phosphate	✔	✔
Sulfate	✔	✔
Ammonia	✔	
Total Kjeldahl Nitrogen	✔	
Fecal Coliform Bacteria	✔	
Biochemical Oxygen Demand	✔	

Use of Standards for Comparative Purposes

One of the most challenging problems in the water quality field today is the establishment of a standard. A reference point must be designated to provide a basis for water quality degradation. Current regulatory standards have set levels that are based on health risk and exposure to harmful pollutants. However, establishing standards in this manner does not account for watershed specific characteristics that may or may not be related to man's impact on nature. For example, a water quality that has not exceeded set regulatory standards may still be adversely impacted by land use changes due to activity by man. Conversely, in some areas natural hydrologic and geologic phenomena may contribute to a water quality degradation that exceeds regulatory standards.

Regulatory standards are effective indicators in regards to whether or not the quality of water is healthful to humans; however, they are not necessarily a standard by which to judge whether or not water quality is being degraded. What is needed is a standard to indicate whether or not water quality in a particular watershed is being degraded. To do this, a local standard (or land use) must be used to provide a baseline water quality to which other land uses can be compared. The premise for such a local standard is that it must be representative of the best water quality attainable for the watershed under study. Ideally the local water quality standard used would be from a land use unimpacted by man. Such a land use could be a native forest, meadow, field or any combination thereof as long there has been little to no activity by man within a significant period of time. This approach is limited on an areal basis in that both the reference watershed and the watershed(s) being compared must possess similar hydrologic and meteorological components. The definition of a local standard was outside the scope of this project.

Stream Sampling and Location

Sample sites were implemented for this project at the outlets of five land use sub-watersheds. The fifth sub-watershed, the agricultural land use, was added late in the project. At the start of the project all samples were taken on a timed basis.
As computer control was added, each site was sampled flow proportionally based on hydrograph slope with the exception of the woodland subwatershed. This site was left on a timed basis due to equipment limitations. This site was selected over the other subwatersheds for timed sampling because initial sample data showed relatively consistent constituent loading.

Two important factors that were considered were dilution due to flow increases and the effect of watershed size. Since the rural, mixed, and urban land uses are situated sequentially along Sweetwater Creek, pollutant concentrations in the stream were proportional to the watershed area of each land use and the amount of flow existing at the sampling point. In addition, the water quality values obtained at each sampling site represented the amount of pollutants coming off the entire watershed above that sampling point.

In order to determine the amount of pollutants added by each land use, the pollutant mass at the watershed outlet was subtracted from the mass above the land use. This change in mass was the amount of pollutant added by that particular land use. The flows used in calculating mass per area were an average for each land use over each season. As a result, calculated numbers tended to underestimate the actual mass of pollutants during higher flows related to storm events.

Seasonal fluctuations in the water table also resulted in changes to watershed hydrology. Base flow dropped significantly between the drier months of April and September, providing a wet season and a dry season. This drop in flow could have resulted in higher pollutant concentrations which may have skewed the results.

System Performance in the Field and Data Analysis

Rainfall and Pollutant Loading

Daily rainfall information was provided by the Town of Sweetwater and was collected at the wastewater treatment plant. Figure 14 displays rainfall amounts for the duration of this project. Rainfall intensity and storm durations were not obtained but would have been extremely helpful in evaluating the data collected and correlating that data with system performance. Tipping bucket rain gages were installed late in the project and an insignificant amount of data was collected by the end of the project.

Loading of selected constituents are displayed in Figures 15 - 24 for 1995 to illustrate the variation in pollutant loading over the course of the project. Figures 20 through 24 represent grab samples only. These figures show clearly that pollutant levels tended to

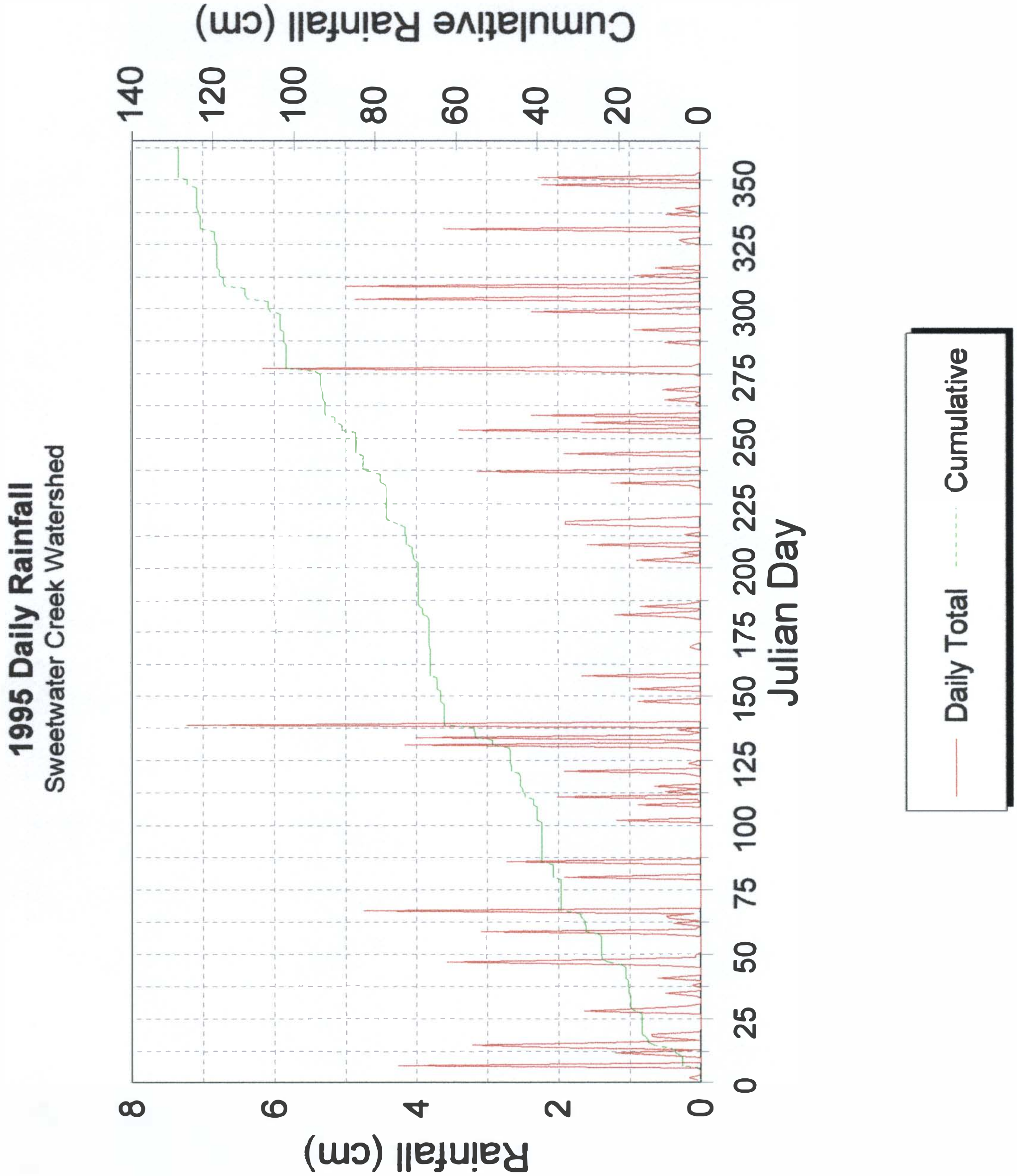

Figure 14: Cumulative and daily rainfall information was collected at Sweetwater, TN.

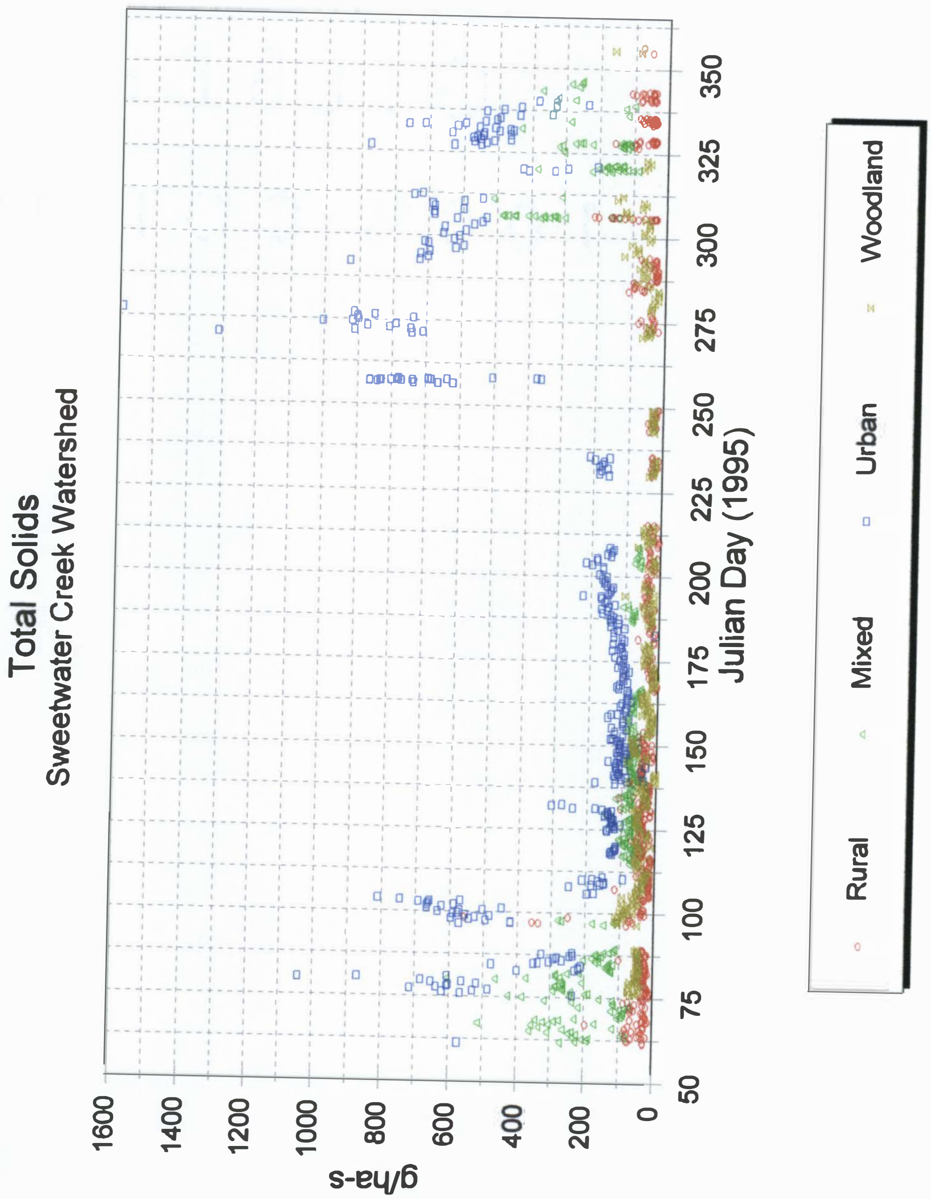

Figure 15: Mass loading was calculated based on the sample results for total solids.

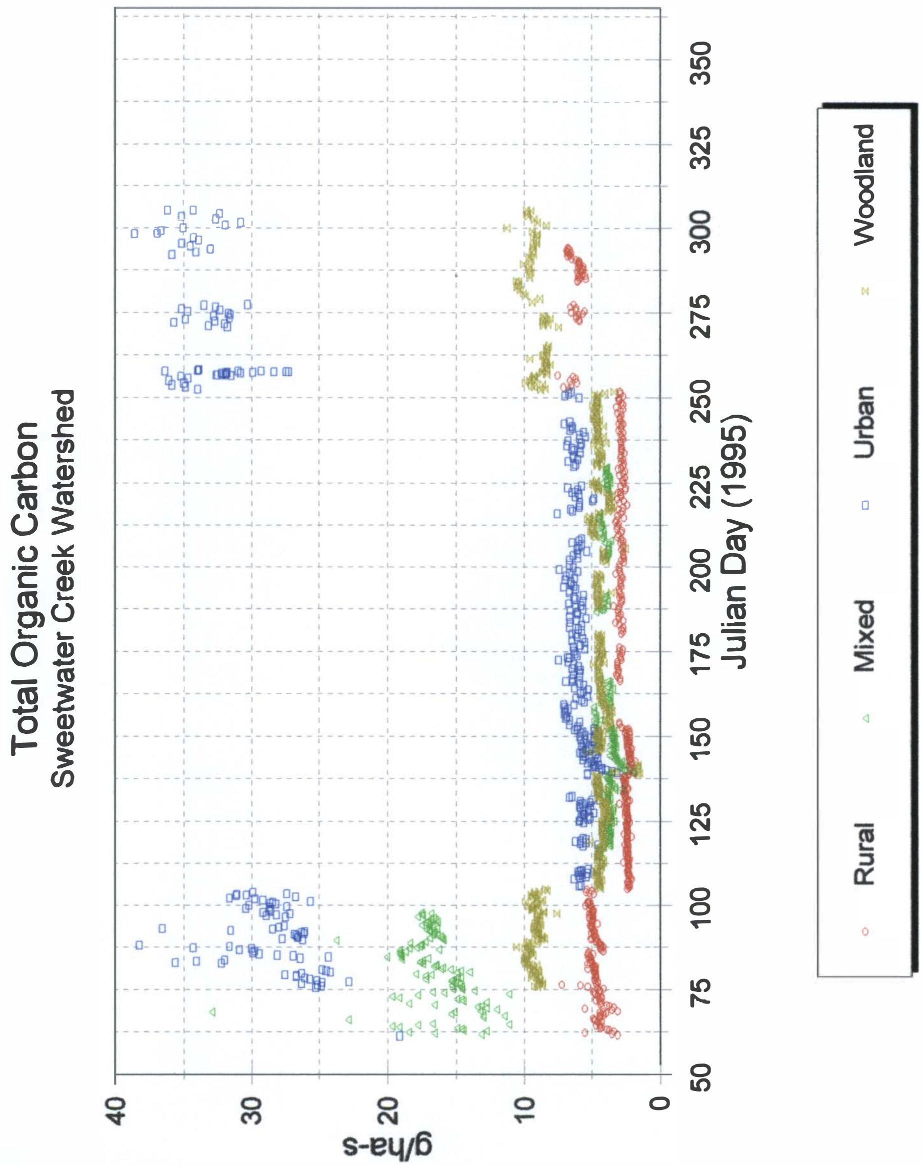

Figure 16: Mass loading was calculated based on the sample results for total organic carbon.

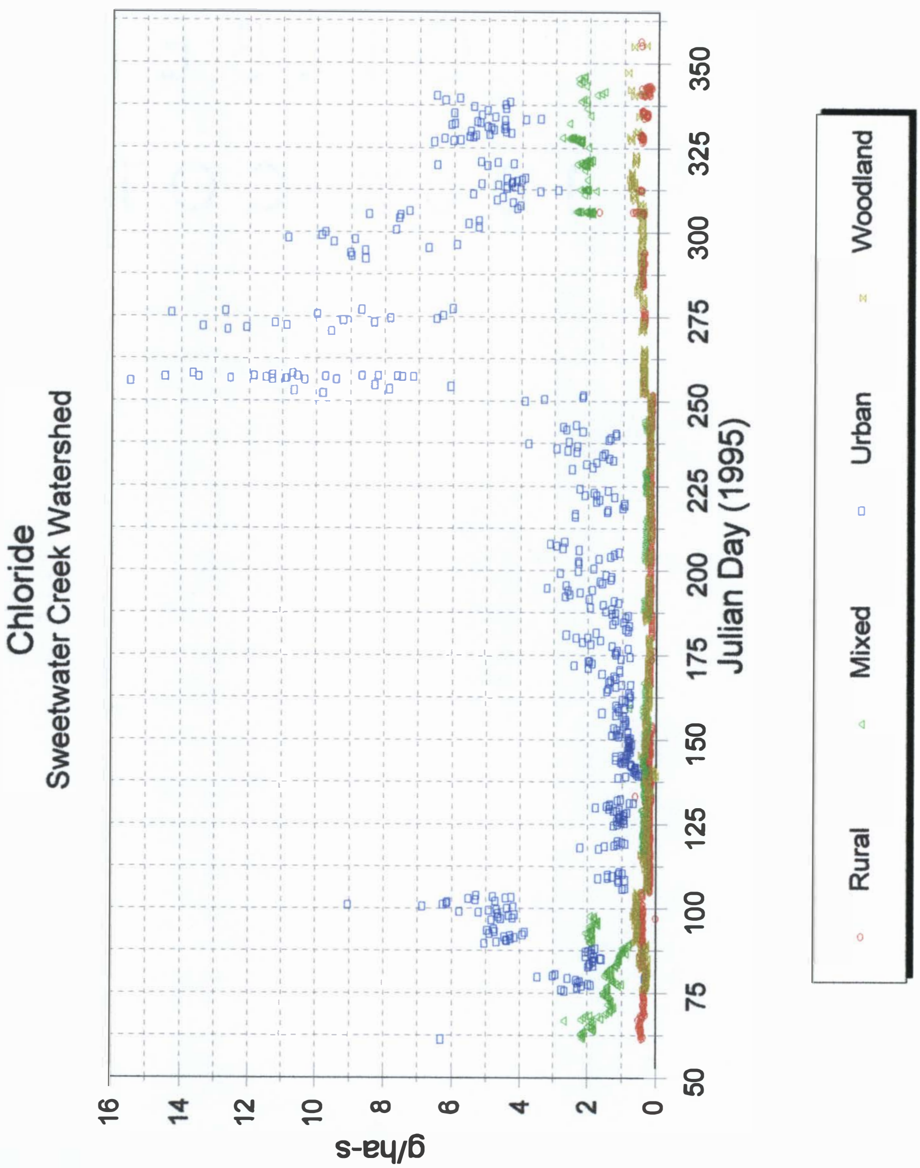

Figure 17:Mass loading was calculated based on the sample results for chloride.

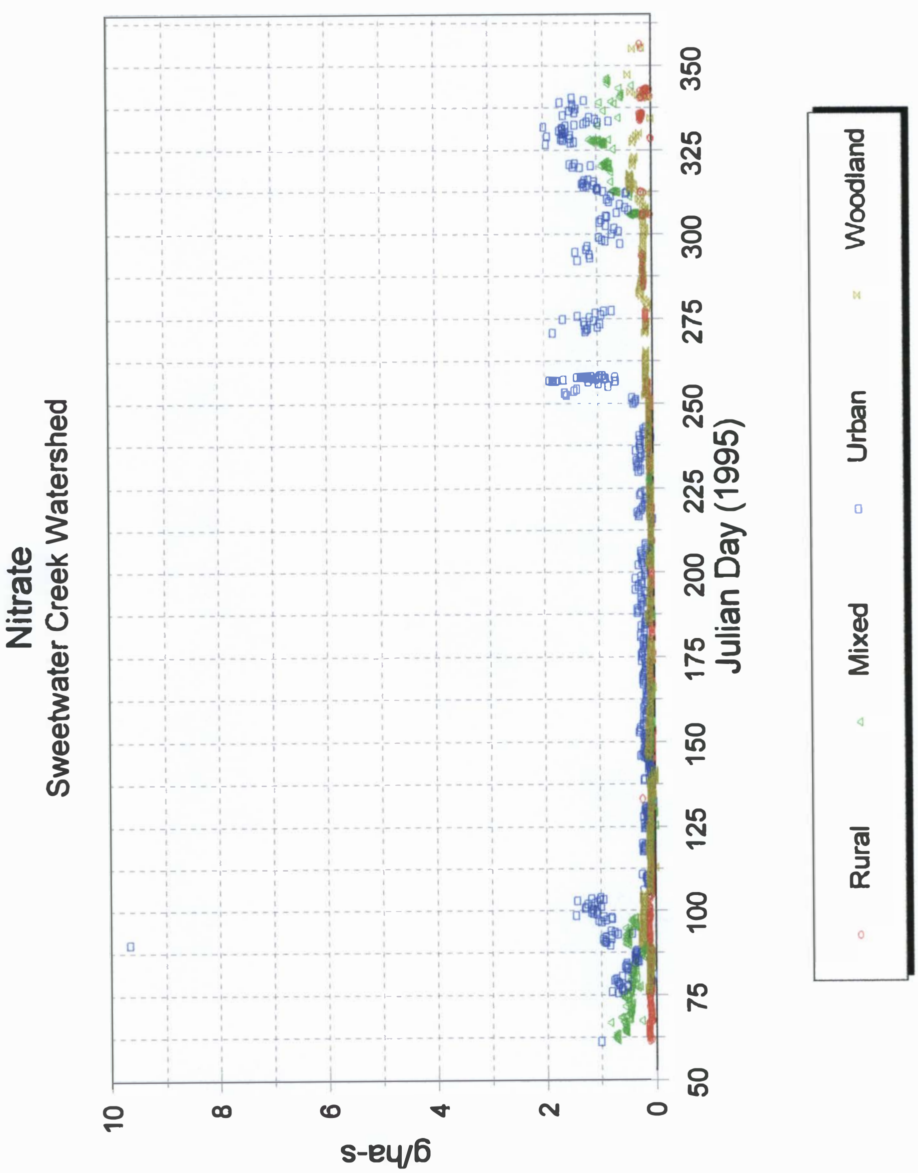

Figure 18: Mass loading was calculated based on the sample results for nitrate.

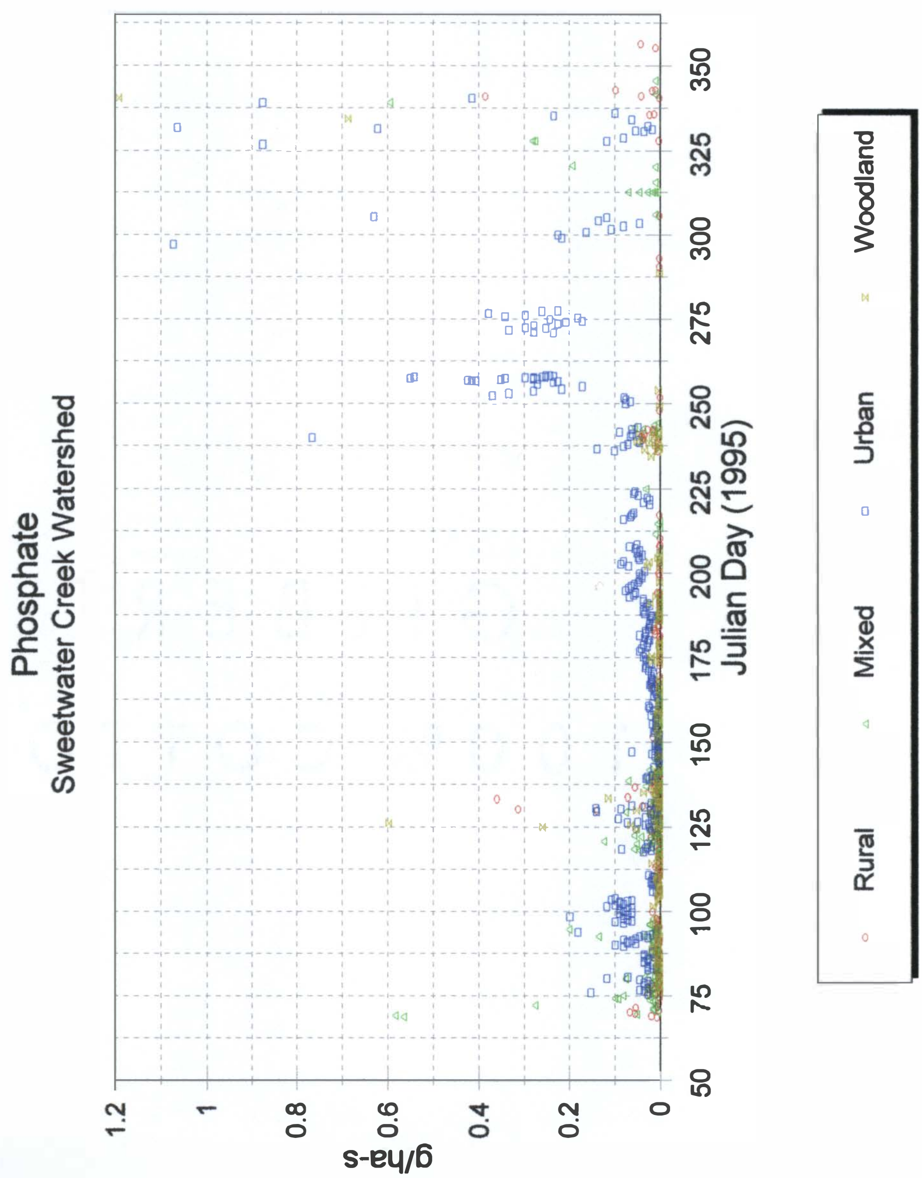

Figure 19: Mass loading was calculated based on the sample results for phosphate.

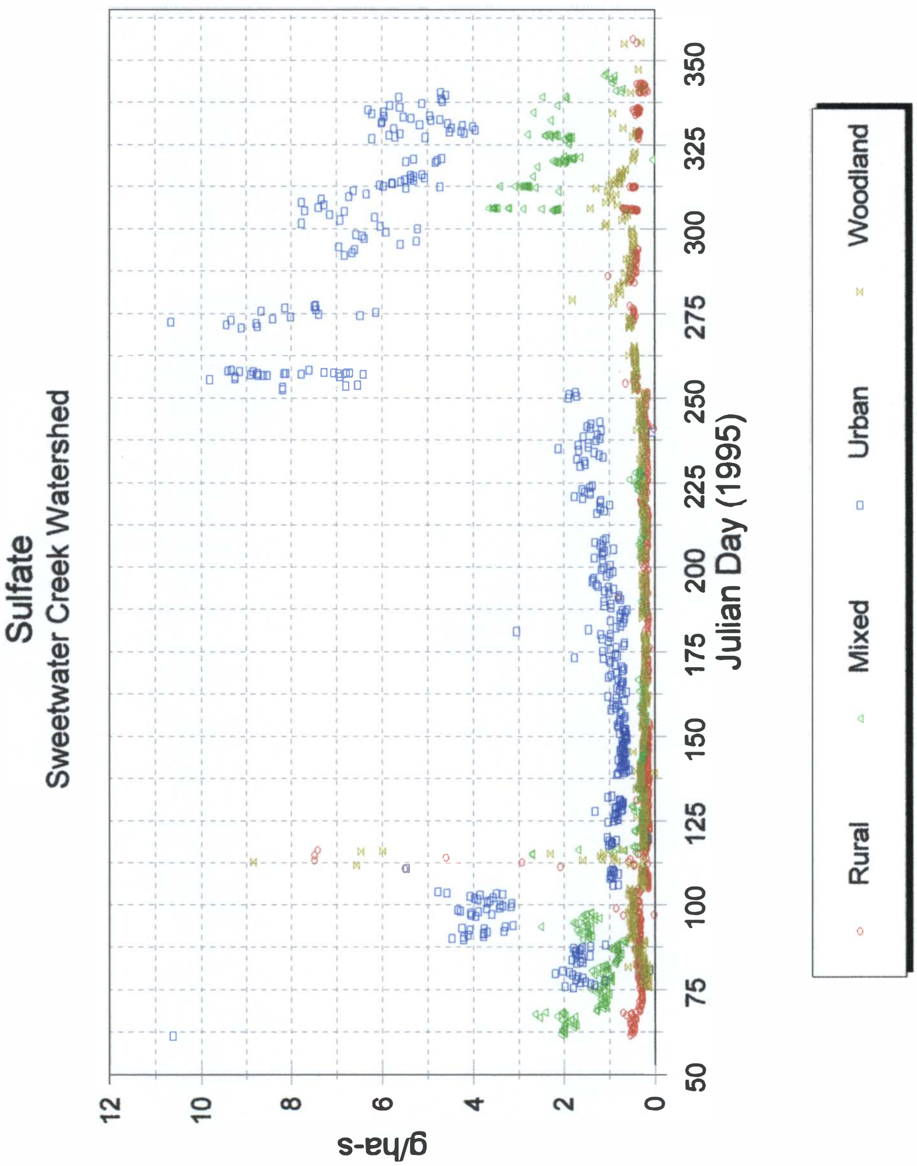

Figure 20: Mass loading was calculated based on the sample results for sulfate.

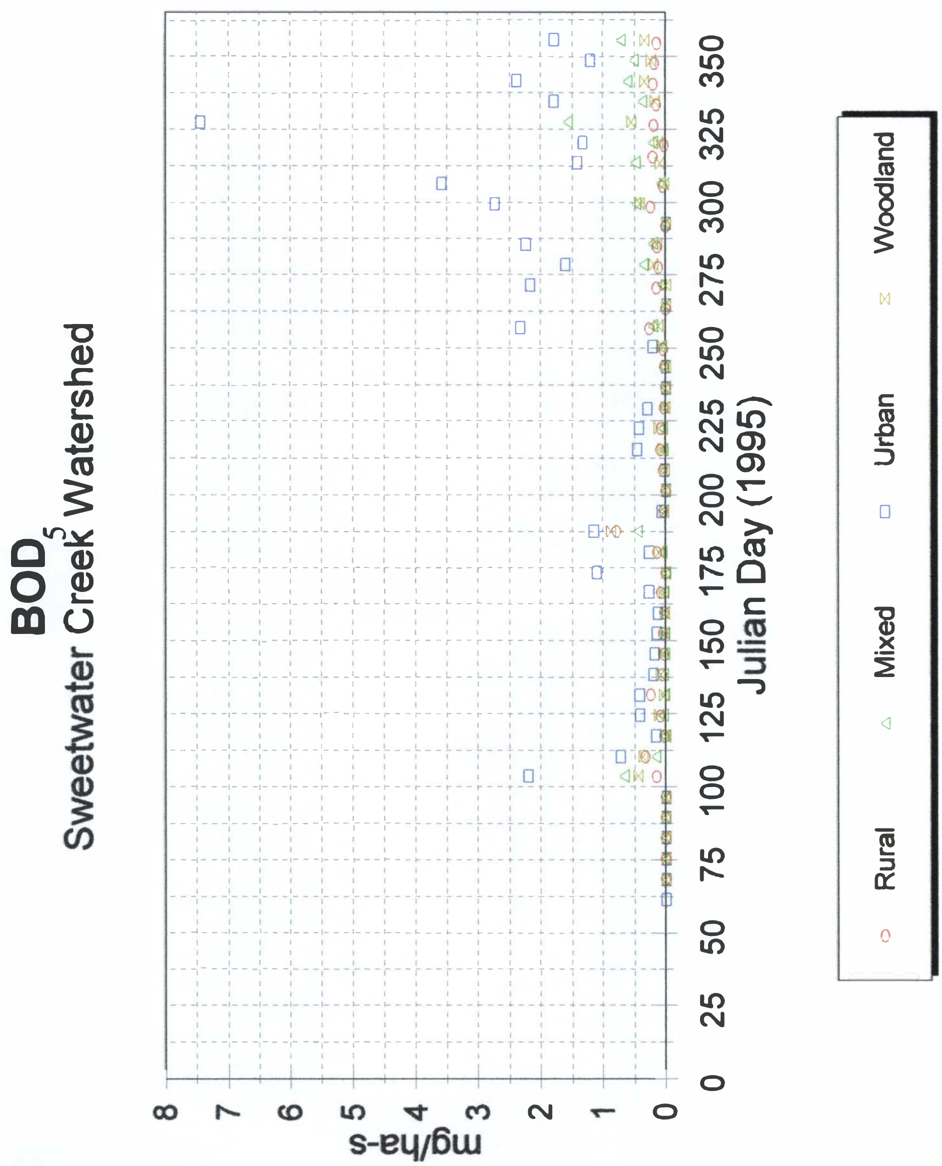

Figure 21: Mass loading was calculated based on the sample results for biochemical oxygen demand (BOD_5).

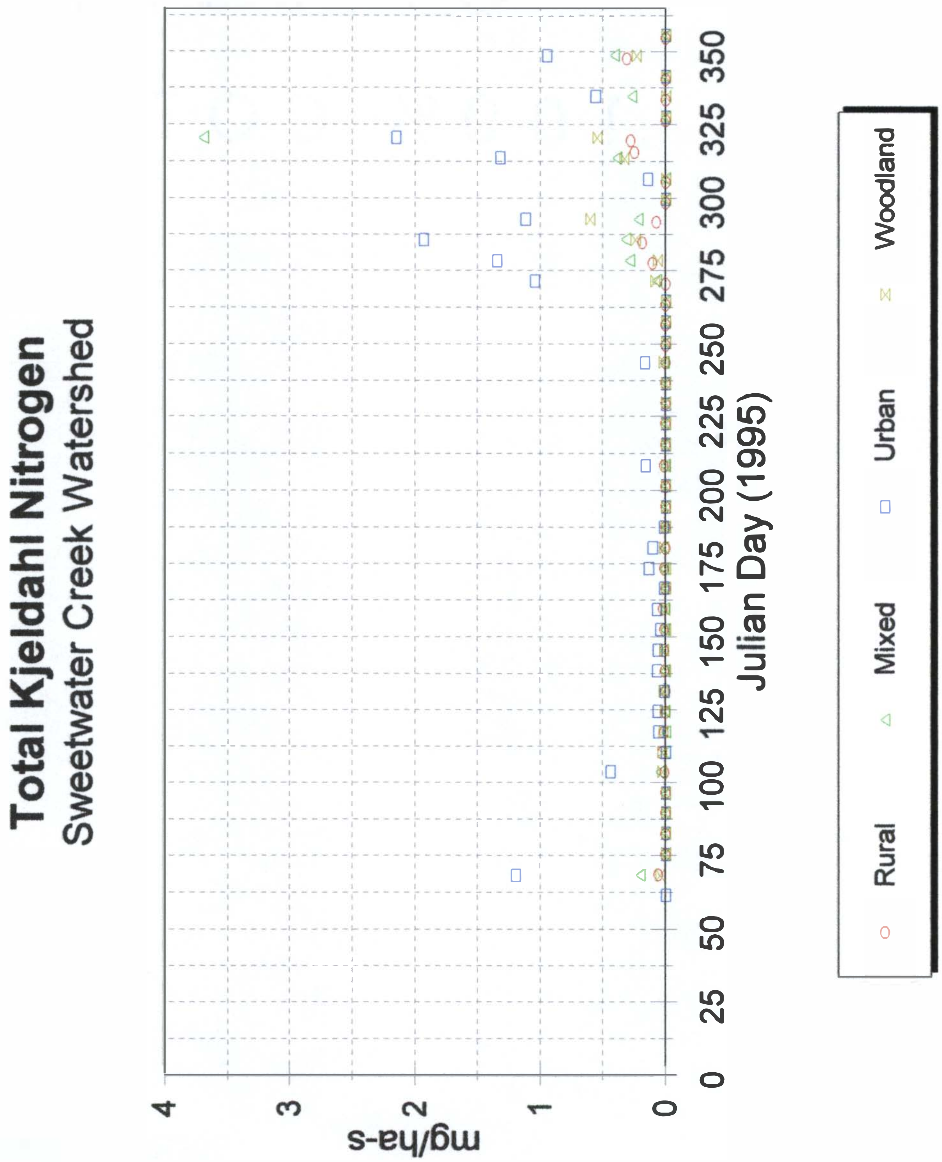

Figure 22: Mass loading was calculated based on the sample results for total Kjeldahl nitrogen.

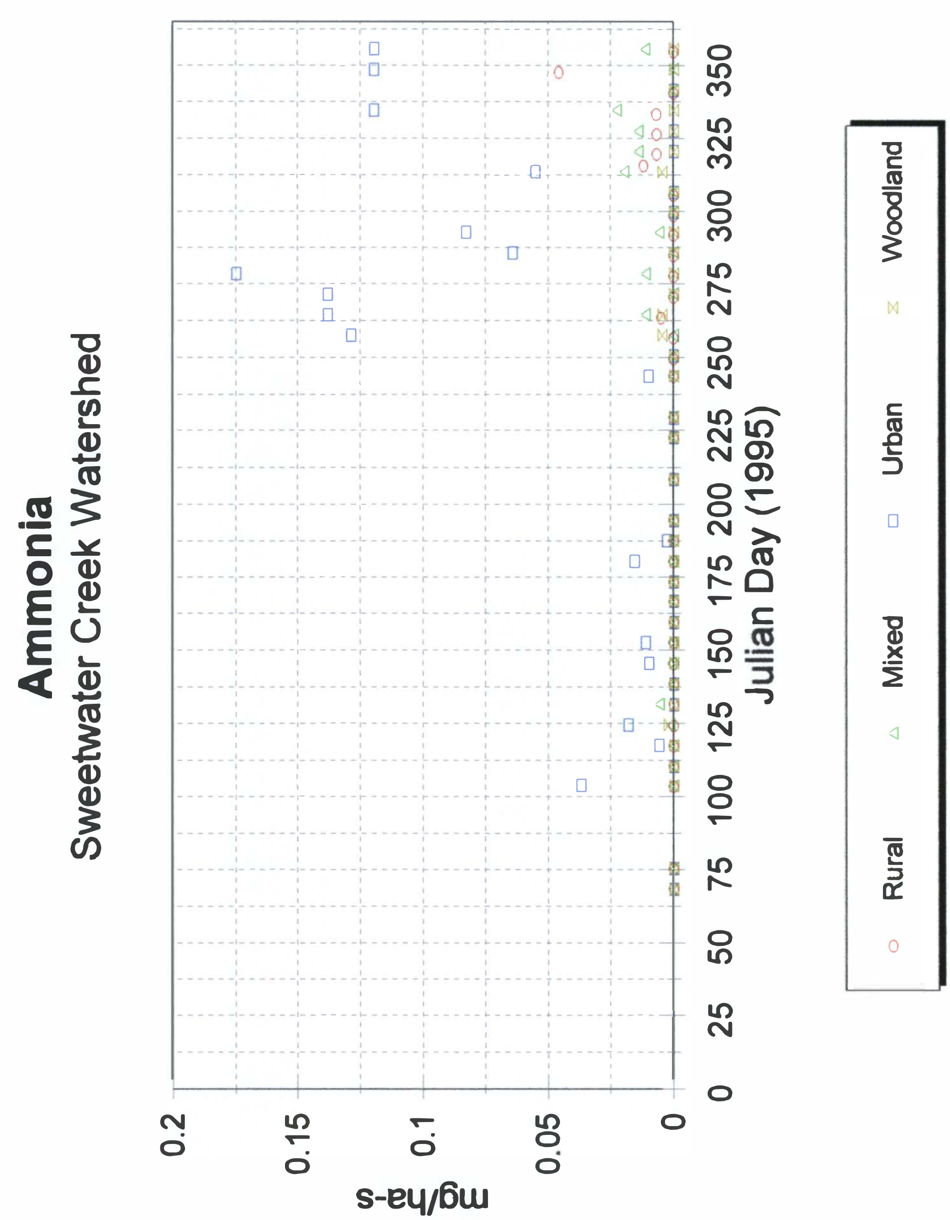

Figure 23: Mass loading was calculated based on the sample results for ammonia.

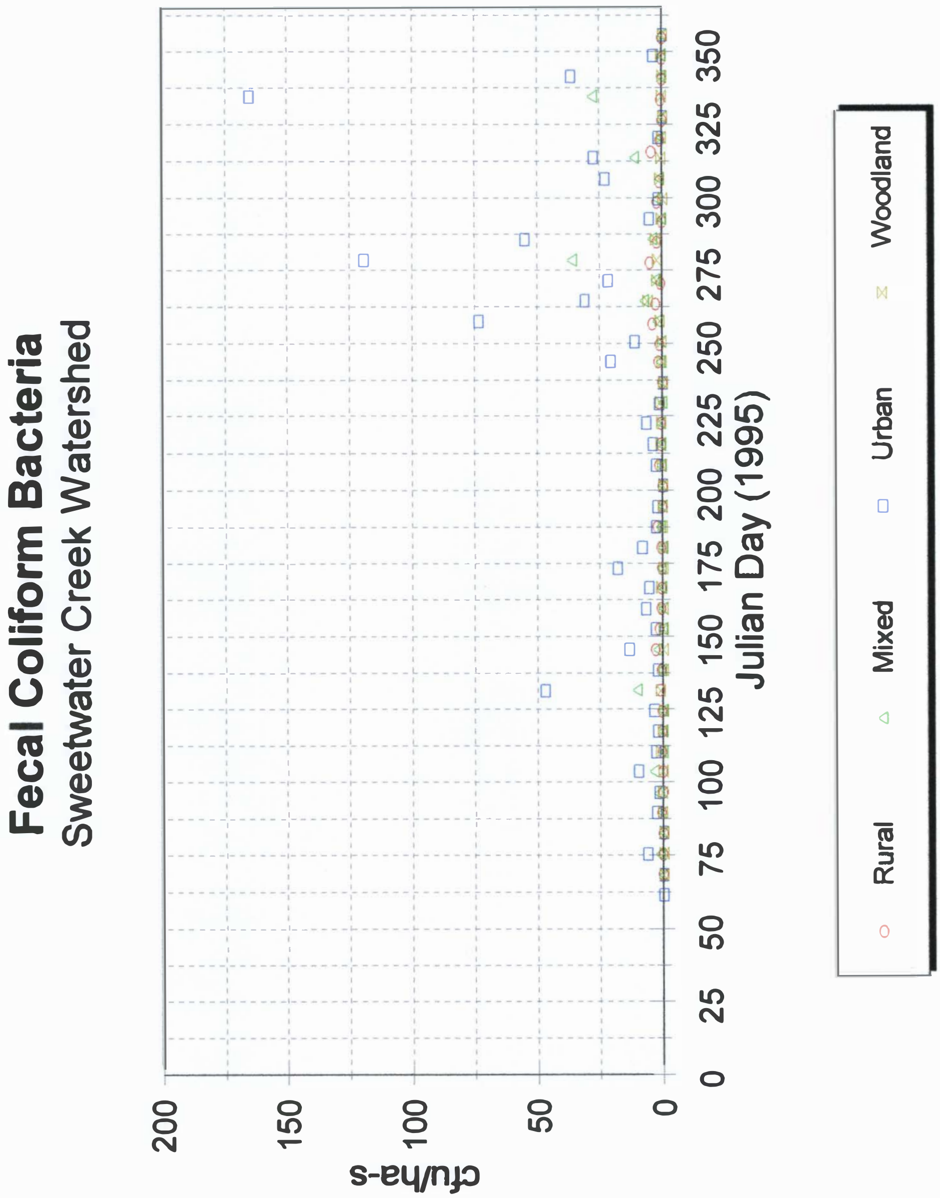

Figure 24: Loading was calculated based on the sample results for fecal coliform.

increase during rainfall events. Tables 6 and 7 display grab sample and automated sample constituent averages and standard deviations for each sampling location (land use), respectively. These descriptive statistics are helpful in pointing out that the standard deviations are fairly high. It is likely that, had the sampler worked as well in the field as it had in the lab, that the standard deviations would have been significantly lower. Further refinement of the sampling system controller for field use is needed in order to obtain more meaningful data.

Evaluation of Sampling System Performance in the Field

Due to the problems associated with the single board computer, the ability of the sampling system to accurately quantify storm pollutant loading in the field was never realized. The pollutant loading displayed in these figures does not necessarily assess the degree of pollution occurring during storm events due to a significant gaps in the data. The number of samples taken did not necessarily increase during storm events. In some cases the samplers appeared to perform within normal operational parameters; however, at no time did all samplers perform optimally for a given storm.

Based on the data obtained during the field testing, the sampling system used to monitor NPS pollution had a number of shortcomings. These shortcoming were not the result of the strategy and sampling technique used but were more related to the components selected for the sampling system.

Grab Sample Averages and Standard Deviation

Land Use	Total Solids Average (g/ha)	Total Solids Std. Dev. (g/ha)	TOC Average (g/ha)	TOC Std. Dev. (g/ha)	Chloride Average (g/ha)	Chloride Std. Dev. (g/ha)	Nitrite Average (g/ha)	Nitrite Std. Dev. (g/ha)	Nitrate Average (g/ha)	Nitrate Std. Dev. (g/ha)	Phosphate Average (g/ha)	Phosphate Std. Dev. (g/ha)	Sulfate Average (g/ha)	Sulfate Std. Dev. (g/ha)
Woodland	27.3	23.9	5.3	3.0	0.39	0.22	0.00031	0.0020	0.15	0.10	0.0069	0.026	0.41	0.28
Rural	30.3	33.1	3.3	1.9	0.29	0.17	0.00046	0.0022	0.10	0.082	0.0016	0.0039	0.28	0.22
Mixed	117.3	143.3	9.4	7.6	1.2	0.89	0.0021	0.0088	0.36	0.33	0.0049	0.012	1.2	1.0
Urban	240.3	312.8	13.7	13.3	4.0	3.2	0.0055	0.031	0.60	0.49	0.071	0.093	3.4	3.0

Land Use	Ammonia Average (mg/ha)	Ammonia Std. Dev. (mg/ha)	TKN Average (mg/ha)	TKN Std. Dev. (mg/ha)	Fecal Coliform Average (cfu/ha)	Fecal Coliform Std. Dev. (cfu/ha)	BOD Average (mg/ha)	BOD Std. Dev. (mg/ha)
Woodland	0.00029	0.0011	0.035	0.093	0.64	1.0	0.15	0.20
Rural	0.0015	0.0064	0.027	0.068	1.0	1.8	0.12	0.13
Mixed	0.0054	0.021	0.11	0.49	3.8	12.5	0.24	0.32
Urban	0.030	0.068	0.29	0.56	16.4	32.1	1.1	1.3

Table 6: Grab samples were averaged and standard deviations calculated for the data collected.

Automated Sample Averages and Standard Deviation

Land Use	Total Solids		TOC		Chloride		Nitrite		Nitrate		Phosphate		Sulfate	
	Average (g/ha)	Std. Dev. (g/ha)	Average (g/ha)	Std. Dev. (g/ha)	Average (g/ha)	Std. Dev. (g/ha)	Average (g/ha)	Std. Dev. (g/ha)	Average (g/ha)	Std. Dev. (g/ha)	Average (g/ha)	Std. Dev. (g/ha)	Average (g/ha)	Std. Dev. (g/ha)
Woodland	39.4	36.3	5.2	3.0	0.34	0.17	0.0013	0.0047	0.12	0.079	0.0076	0.063	0.40	0.60
Rural	38.4	43.3	2.5	2.0	0.31	0.15	0.0012	0.0048	0.093	0.061	0.0046	0.025	0.34	0.56
Mixed	138.7	127.2	5.2	6.5	1.3	1.1	0.0052	0.018	0.42	0.45	0.014	0.054	1.2	0.99
Urban	278.2	276.8	11.3	12.4	3.7	3.0	0.014	0.038	0.67	0.69	0.07	0.13	3.1	2.6

Table 7: Automated samples were averaged and standard deviations calculated for the data collected.

The field testing revealed that single board computers that were used did not stand up to the rigors of the environment. Data collection would cease due to a system error resulting from temperature and humidity extremes. Since data collection were downloaded weekly, there were times that an entire week of data was not collected due to a system shut-down.

In addition, the programming capability of the single board computer was not as robust as desired. The programming language, CAMBASIC, is essentially a simplistic version of the BASIC language. The number of commands and keywords used by CAMBASIC are limited; as a result, a simplistic program could become quite complex due to programming constraints. Increased flexibility was desired in managing system components and data storage/manipulation.

Various land uses were selected as sub-watersheds to evaluate the sensitivity of the sampling system and to understand what changes might need to be made to the system for a specific monitoring condition. A sampling system monitoring an area with minimal runoff may require different components or programming to achieve the level of accuracy realized in watersheds with significant runoff. A field sensitivity analysis was not completed due to the problems with the single board computer.

In collecting nonpoint source pollution data from land uses the target is to sample such that the runoff component of the streamflow can be characterized. If the runoff component cannot be characterized, the samples that are obtained may be skewed. This skew occurs because the samples obtained at baseflow (during non-storm events) are not necessarily characterizing any runoff. Since runoff usually occurs during storm events, the data collected at baseflow at best represent pollutant contributions due to groundwater interaction, stream channel erosion, point sources, and other mechanisms that are more stream specific than they are land use specific. Because of the malfunction of the single board computer in the field, the data collected could not be separated into storm event data and baseflow data. This may result in the data being skewed; however, it is impossible to determine this until additional sampling is performed that can be separated into storm and baseflow data. The data provided in this thesis should be treated as preliminary data until future sampling can confirm the findings that are presented.

Chapter 7

Conclusions and Recommendations for Future Research

In performing water quality research, one must recognize that no single study provides definitive answers on the whole. However, further study on how NPS pollution is monitored from a variety of studies will go far in explaining the mechanisms of water quality degradation. Additional research is needed in order to build on what has already been accomplished.

The monitoring strategy established for the project provided a decision making and procedural framework that was successful in carrying the project to the monitoring phase. The scope of the strategy is rather broad and future research efforts should focus on making the strategy more specific to the project.

The sampling system developed for this project performed admirably in the lab and less than satisfactorily in the field. Laboratory testing performed on the sampling system provided excellent results. Field testing proved challenging due to the use of a single board computer that did not stand up well to the environment. Therefore, the substandard performance of the sampling system in the field was due to component selection rather than the programming and operational design of the system. Future research efforts should focus on hardware selection more appropriate to the environmental extremes that may be encountered. In addition, more research should be done to expand the system capability (e.g., computer control of two or more samplers to provide greater flexibility and sampling capacity).

In conclusion, man's impact on the environment depends on the degree of land development and the management practices employed that contribute to increases in runoff potential. Proper land management in areas subject to high runoff potential should greatly reduce the contribution of pollutants to streams. Proper monitoring and management of the mechanisms driving NPS pollution such as green space management, installation of riparian zones along streams, hydrology restoration in disturbed areas, and stormwater control and treatment are paramount in reducing the impacts of pollution.

A full analysis of nonpoint source land use impacts on water quality should be evaluated. Further research is needed to discover how sampling location within the stream affects sample variation. Hydrologic aspects in analyzing water quality should be examined to discover how rainfall intensity and rainfall amount can be correlated to pollutant concentrations in the stream. More extensive research should be performed on surface and groundwater interaction and the role it might play in water quality degradation.

Overall, this project has provided an excellent starting point for continued nonpoint source monitoring research. A sampling system has been developed that will allow for the primary driving force behind nonpoint source pollution, runoff, to be quantified with greater precision and for pollutants to be analyzed from samples taken at times when the potential for pollution is highest. The monitoring strategy described here is one that regulatory agencies and researchers alike can utilize in making critical decisions on how to monitor and reduce NPS pollution.

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Appendices

Appendix A

Stream Flow Calculation Procedure

Stream velocity measurement was done with a Marsh-McBirney velocimeter. The procedure used to calculate flow was taken from the Open Channel Profiling Handbook published by Marsh-McBirney.

Step 1: Select a stream cross-section that has relatively uniform flow through it. Avoid cross-sections near stream turns or other sources of eddying and turbulence as this will result in incorrect readings.

Step 2: Survey the stream cross-section using a level to ensure that the stream channel is relatively uniform (i.e., no permanent debris or extremely abrupt depth changes within the channel cross-section). Proper channel cross-section selection will help reduce possible error later when calculating flow.

Step 3: Measure the channel and divide the width into seven equal segments. The difference between the average velocities of any two adjacent segments should not be greater than 10%. If so, the number of segments should be increased to reduce variability and improve overall accuracy.

Step 4: At the center of each segment measure the stream depth and calculate three velocity measurement positions by multiplying the depth by 0.2, 0.6, and 0.8.

Step 5: Measure the velocity at each of the three positions calculated in Step 4. Be sure to measure the 0.2, 0.6, and 0.8 positions **from the surface of the stream**. When taking a measurement, be sure to hold the measurement probe in a stationary, vertical position to reduce variability.

Step 6: Calculate the average for the 0.2 and 0.8 velocities. Then average the 0.6 velocity with the 0.2 and 0.8 velocity average to obtain the overall average velocity for that stream segment.

Step 7: Calculate the area for each segment by multiplying the depth time the segment width. For trapezoidal segments, equation A-1 can be used. Figure A-1 displays a typical trapezoidal cross-section including the variables given in Equation A-1.

$$Area = \left(\frac{x+y}{2}\right) * Width \qquad \text{[Eqn. A-1]}$$

Step 8: Determine the flow in each segment by multiplying the segment velocity segment area. Then add all segment flows together to obtain total stream flow.

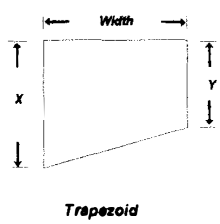

Figure A-1: A typical trapezoidal cross-section used in calculating stream flow.

Appendix B

Tennessee Fluid Level Indicator (TFLI)

Theory

The TFLI uses Archimedes principle of buoyancy to establish a relationship between force and depth. A buoyant force acts upon any object placed in a fluid. If the buoyancy force is greater than the weight of an object, it will float. The equation describing the buoyancy force, given by Munson et al. (1990), is

$$F_b = \rho * g * V, \qquad \text{[Eqn. B-1]}$$

where, ρ is the fluid density,
g is the gravitational force,
V is the submerged volume of the object.

The TFLI is a weighted cylindrical tube that is placed in the water and attached to a load cell. As noted above, the buoyant force acting on the tube will increase or decrease depending on its submerged volume. It should be noted that the TFLI is designed so that the tube weight will always be greater than the buoyant force acting on it. As a result, the submerged volume now becomes dependent on the height of the tube (or depth of water). This can probably be seen in a clearer sense with the following mathematical derivation. Summing the forces acting on the tube (See Figure B-1) gives the following equation,

$$F = W - F_b, \qquad \text{[Eqn. B-2]}$$

where F is the resultant force,

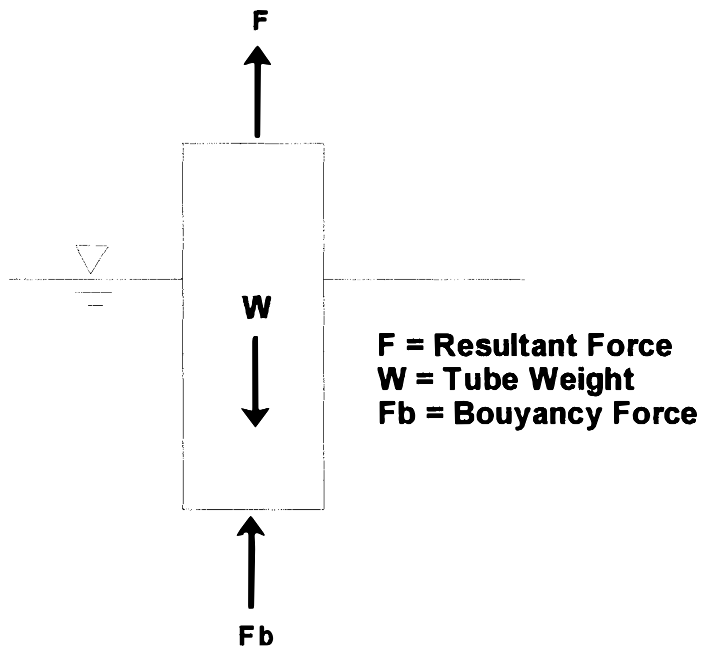

Figure B-1: A free-body diagram displays the forces acting on the weighted tube of the TFLI.

W is the weight of the tube,

F_b is the buoyancy force.

Substituting Eqn. B-1 into Eqn. B-2 gives

$$F = W - \rho*g*V, \qquad \text{[Eqn. B-3]}$$

but the submerged volume (V) can be defined by the geometrical properties of the tube

$$V = \pi*r^2*h, \qquad \text{[Eqn. B-4]}$$

where, $\pi = 3.14$,

r = outer tube radius, and

h = submerged tube length.

Note that if the end of the tube is placed near the bottom of the stream the submerged tube length, h, is also the water depth. Substituting Eqn.B- 4 into Eqn. B-3 gives

$$F = W - \rho * g * \pi * r^2 * h \qquad \text{[Eqn. B-5]}$$

where all variables except for F and h are known.

The resultant force (F) described by equation B-5 is the tube weight minus the buoyancy force and will always be positive. A negative or zero resultant force means that the tube is floating. This is not desirable because the resultant force is what is being measured to establish flow depth. It was stated above that the tube was weighted. This was done primarily to ensure that the tube would be stable and to make the tube weight greater than the buoyancy force acting on it. Stability is achieved by making certain that the center of gravity of the entire tube is close to the centroid of the submerged portion of the tube. Figure B-2 shows that an undesired moment exists when the center of gravity is too far from the centroid of the submerged volume. Placing a weight in the bottom of the tube effectively brings the center of gravity closer to the centroid.

Components

A load cell was used to measure the resultant force. By attaching the tube to the load cell, weight change in the tube could be measured as the water depth changed.

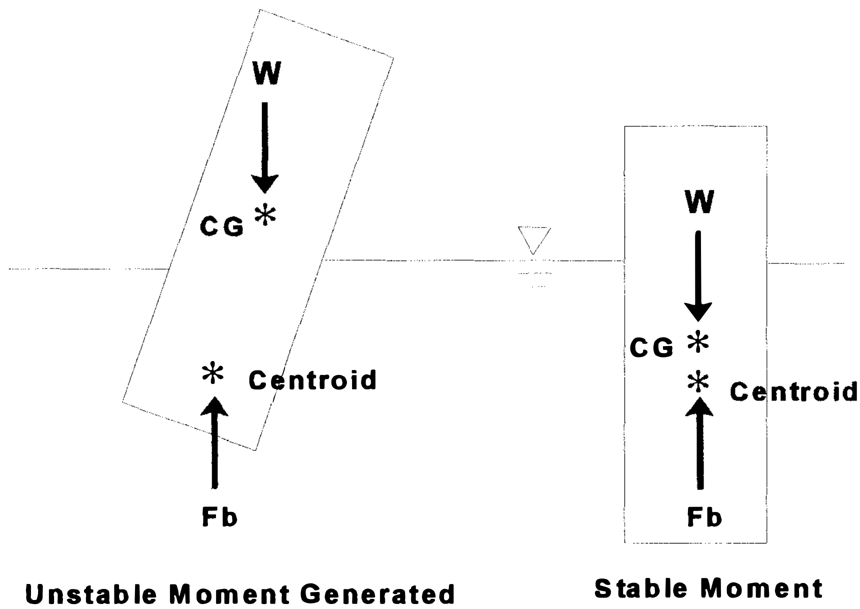

Figure B-2: Effect on tube's center of gravity by weighting the tube.

The load cell was comprised of four strain gages wired in a full Wheatstone bridge configuration and excited with 8 volts. Applying a load changed the resistance in the strain gages and the output voltage from the bridge. The output signal, in millivolts, was amplified to a maximum of 5 volts so it could be read by the single board computer.

The buoyancy tube was hung from the load cell such that it had some freedom of movement; however, the tube was essentially plumb. The capacity of the load cell was based on the maximum weight that could be applied to it. For the TFLI, load cell size depended on the entire tube weight. For Sweetwater Creek 4.5-kg and 9.1-kg (10-lb and 20-lb) load cells were used with a tube length of 1.2 m and 1.5 m (4 and 5 ft), respectively. The buoyancy tube was placed in a stilling well to cancel any horizontal forces such as stream current or wind. The stilling well was a larger diameter PVC tube with an opening near the bottom to allow water to flow into it. Keeping the buoyancy tube a short distance from the bottom of the stilling well allowed for some sedimentation to occur without hindering operation of the TFLI. Stilling wells were supported in the stream by securing them to steel fence posts driven into the stream bed.

Calibration

The TFLI was connected to the 5081 Microcontroller to store readings from the load cell. Load cell readings are in volts, therefore; the TFLI was calibrated before installation to determine the relationship between load cell output and depth. The calibration involved slowly filling and then emptying the outer tube or stilling well portion of the TFLI. Millivolt readings were taken at 0.031 m (0.1-ft) increments.

The voltage to depth relationship was derived by simple linear regression of the load cell output and corresponding depth in a spreadsheet and obtaining a mathematical equation. This calibration equation was used by the computer to compute stream depth at each sampling site.

Accuracy

The TFLI was tested in both static and flowing bodies of water for accuracy. Testing was performed in a laboratory setting so that all parameters could be controlled. Testing in flowing water was performed via a raceway that contained a stilling well in which the entire TFLI set-up was placed. A 1.2-m (4-ft) TFLI (4.5-kg or 10-lb load cell) was used for testing since it is the size used most frequently in this research.

In a static body of water the full scale error was found to be 0.2% or 0.24 cm. Error increased to 0.8% or 0.91 cm (0.03-ft) when the TFLI was in a flowing body of water encased by the stilling well. This increase was most likely due to vibration and slight motion of water within the stilling well. Rough measurements in the field showed this value to be slightly higher when the TFLI was placed in an actual stream. It was estimated that field measurements were accurate on the order of 1.2% or about 0.15 cm (0.05-ft). Most other depth measurement devices are accurate to within 0.3 cm (0.01-ft); however, the TFLI's accuracy is adequate for most applications.

The TFLI was also examined at a wide range of temperatures for accuracy. Over a 33 °C range of temperature full scale error was about 0.7%, which equates to about 0.061 cm (0.02-ft). Since this is a much wider temperature range than would normally be encountered, it is expected that error due to temperature variation would be less than half of this value, about 0.3% or 0.03 cm (0.01-ft).

Appendix C

Sampling Control Computer Program

Note: Program written in a version of BASIC called CAMBASIC.

```
3 PULSE = 0
4 CNT = 0
5 CONFIG PIO 0,0,0,0,1,1
6 V = 0
7 SETVOL = 756000
8 VOL = 0
10 P% = &1900
15 QC = 35
20 MAXSAMP = 120
22 TPEAK = 237.6
24 QPEAK = 290
26 BASE = 756000
50 T$ = TIME$(0)
55 HR$= RIGHT$(T$,5)
60 MN$ = RIGHT$(T$,2)
65 PTM = CTM
67 DELAY 29
70 CTM = VAL(HR$)+VAL(MN$)/60
75 T = VAL(T$)*100 +VAL(HR$)
77 BIT 1,0,ON
78 DELAY 1
80 FOR X = 1 TO 600
90 CNT = CNT + 1
100 VT = AIN!(1,0,1)
105 BT = BT+VT
110 DELAY .1
115 NEXT X
120 BIT 1,0,OFF
130 AVE = BT/CNT
135 CNT = 0
137 BT = 0
140 H = (-(5 /255)*13.751 *AVE+57.361)/12
150 PRINT "Read flow."
155 Q2 = QC
160 QC = ABS(.0615 -25.84 *H+23.89 *H^2 -3.27 *H^3)
```

```
180 DT = ABS(CTM-PTM)
190 X = (ABS(QC-Q2)*TPEAK)/(DT*QPEAK)
195 PRINT " Volt      Depth      Flow       Slope     Volume"
200 VOL = VOL+60 *(QC*DT)
205 PRINT AVE, H, QC, X, VOL
215 MULT = (3600 - 3598 *((X-.2)/(2 -.2)))/3600
220 IF X > 2 THEN MULT = 1 /1800
225 IF X < .2 THEN MULT = 1
230 IF PULSE > 100 THEN SETVOL = BASE ELSE SETVOL = BASE*MULT
240 PRINT "Set Vol. =",SETVOL
245 IF VOL < SETVOL THEN GOTO 50
247 VOL = 0
250 BIT 1,1,ON
255 DELAY 1
260 BIT 1,1,OFF
270 PULSE = PULSE + 1
272 IF PULSE > 120 THEN GOTO 475
275 PRINT "pulse=";PULSE
280 DPOKE P%,H,1
285 DPOKE P%+2,QC,1
290 DPOKE P%+4,T,1
295 R=AIN!(2,0,1)
300 RG=R*(5 /255)
305 PRINT "rain=";RG
310 DPOKE P%+6,RG,1
315 D$ = DATE$(0)
320 M$ = RIGHT$(D$,8)
325 DY$ = RIGHT$(D$,5)
330 D = VAL(M$)*100 +VAL(DY$)
335 DPOKE P%+8,D,1
340 P% = P%+10
345 VOL=0
350 GOTO 50
475 END
```

Vita

Vita

Bryan F. Staley was born in Bethesda, Maryland on July 28, 1971. He attended schools in the public systems of Maryland, West Virginia and North Carolina. In June 1989, he graduated from East Henderson High School in Flat Rock, North Carolina. He entered North Carolina State University, Raleigh, North Carolina during August of 1989 where in May, 1994 he received the Bachelor of Science in Biological and Agricultural Engineering (soil and water concentration). He entered the Master's program in Biosystems Engineering in August of 1994. In September, 1996 he began work as an environmental and agricultural engineering consultant with a firm in Raleigh, North Carolina. He received his Master's degree in August, 2000.

He is presently working as an independent environmental and agricultural engineering consultant in Raleigh, North Carolina.